GRI-91/0128

STRATIGRAPHY AND DEPOSITIONAL SYSTEMS OF THE FRONTIER FORMATION AND THEIR CONTROLS ON RESERVOIR DEVELOPMENT, MOXA ARCH, SOUTHWEST WYOMING

TOPICAL REPORT
(April 1989 - March 1991)

Bureau of Economic Geology
The University of Texas at Austin

Prepared in cooperation with
The Geological Survey of Wyoming

Contract No. 5082-211-0708

GRI

TGS TIGHT GAS SANDS

Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, Illinois 60631

GRI 91/0128

Stratigraphy and Depositional Systems of the Frontier Formation and Their Controls on Reservoir Development, Moxa Arch, Southwest Wyoming

Topical Report

(April 1989–March 1991)

Prepared by

H. Scott Hamlin

Bureau of Economic Geology
W. L. Fisher, Director
The University of Texas at Austin
Austin, Texas 78713-7508

Prepared in cooperation with

The Geological Survey of Wyoming

for

GAS RESEARCH INSTITUTE
Contract No. 5082-211-0708
Mark Johnson, Project Manager

July 1991

DISCLAIMER

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. GRI-91/0128	2.	3. Recipient's Accession No.

4. Title and Subtitle Stratigraphy and Depositional Systems of the Frontier Formation and Their Controls on Reservoir Development, Moxa Arch, Southwest Wyoming

5. Report Date July 1991

6.

7. Author(s) H. Scott Hamlin

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Bureau of Economic Geology
The University of Texas at Austin
University Station, Box X
Austin, TX 78713-7508

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C) 5082-211-0708
(G)

12. Sponsoring Organization Name and Address
Gas Research Institute
9600 West Bryn Mawr Avenue
Chicago, IL 60631
Project Manager:
Mark Johnson

13. Type of Report & Period Covered
Topical April 1989 - March 1991

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

By controlling sandstone continuity and detrital clay content, depositional systems influence reservoir development in low-permeability gas-bearing sandstones of the Upper Cretaceous Frontier Formation along the Moxa Arch in the Green River Basin, southwest Wyoming. Original depositional porosity and permeability are highest in clean Frontier sandstones, which even after diagenetic modification comprise the most prolific reservoirs. The Frontier was deposited in a fluvial-deltaic system, in which most reservoirs lie in fluvial channel-fill and marine shoreface sandstone facies. The fluvial channel-fill sandstones form southeast-trending belts, which are a few miles wide, several tens of feet thick, and separated by interchannel shale and sandy shale. Within the channel belts, clean sandstone occurs as discontinuous lenses up to 20 feet thick that are interlayered and laterally gradational with mud-clast-rich shaly sandstone. The marine shoreface facies forms a continuous northeast-thinning sheet of sandstone, 40 to 120 feet thick. Clean sandstone is best developed near the top of the shoreface facies in northeast-thinning trends 5 to 40 feet thick.

17. Document Analysis a. Descriptors
Wyoming, Green River Basin, Frontier Formation, stratigraphy, depositional systems, tight gas sandstones, reservoir development

b. Identifiers/Open-Ended Terms
stratigraphy of the Frontier Formation, influence of depositional environment on reservoir development, marine shoreface and fluvial channel-fill sandstone facies

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Release unlimited	Unclassified	
	20. Security Class (This Page) Unclassified	22. Price

(See ANSI-Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4-77) (Formerly NTIS-35) Department of Commerce

RESEARCH SUMMARY

Title	Stratigraphy and depositional systems of the Frontier Formation and their control on reservoir development, Moxa Arch, southwest Wyoming
Contractor	Bureau of Economic Geology, The University of Texas at Austin, GRI Contract No. 5082-211-0708, "Geologic Analysis of Primary and Secondary Tight Gas Sands Objectives."
Principal Investigator	S. P. Dutton
Report Period	April 1989 – March 1991 Topical Report
Objectives	To determine the stratigraphic and depositional framework of Frontier Formation sandstones at regional and local scales and to investigate how this framework influences reservoir distribution and quality.
Technical Perspective	Since 1982, the Gas Research Institute (GRI) has supported geologic investigations designed to develop knowledge necessary to efficiently produce natural gas from low-permeability sandstone reservoirs. As part of that program, the Bureau of Economic Geology has conducted research on low-permeability sandstone in the Upper Cretaceous Frontier Formation along the Moxa Arch in the Green River Basin, southwest Wyoming. Stratigraphic studies place reservoirs in the context of a depositional systems framework that allows the identification of productive facies and the determination of lateral continuity of individual sandstone bodies. Field-scale reservoir analyses provide geologic information necessary for engineering simulation studies.
Results	Along the Moxa Arch, the Frontier Formation was deposited in fluvial and wave-dominated-deltaic systems, in which strike-aligned shoreface sandstone and dip-oriented fluvial channel-fill sandstone form the most important reservoirs. Frontier sandstone reservoirs are enclosed in coastal-plain and nearshore-marine shale and sandy shale. The Frontier is divided into several sandstone-bearing intervals. Marine shoreline sandstones in the First (upper) Frontier and the Third and Fourth (lower) Frontier occur only at the north end of the Moxa Arch (La Barge Platform) and are locally productive there. Second Frontier sandstone extends down the length of the Moxa Arch and contains the most prolific gas reservoirs. The Second Frontier is composed of several sandstone benches, of which the First and Second Benches are most widespread. The First Bench comprises laterally discontinuous fluvial channel-fill sandstones, whereas the Second Bench is a single progradational shoreface sandstone having good lateral continuity. The main depositional and stratigraphic controls on distribution and quality of Frontier reservoirs are sandstone continuity and detrital clay

content. On the La Barge Platform, Second Bench upper shoreface sandstone has the lowest detrital clay content and consistently occurs at the top of the laterally continuous shoreface sequence. Most Frontier wells on the La Barge Platform have Second Bench perforations, although variable thickness and diagenetic modification influence the productivity of individual wells. The First Bench contains numerous discontinuous fluvial channel-fill sandstones, each composed internally of a complex arrangement of clay-rich and clay-free zones. Reservoir quality in the First Bench is highly variable, although it improves southward along the Moxa Arch.

Technical Approach

Correlation and interpretation of logs from more than 800 wells and cores from 13 wells established the stratigraphic framework of the Frontier at regional and local scales. Cores were used for interpretation and characterization of depositional facies and for lithologic calibration of well logs. The lateral variability in thickness and continuity of individual sandstone bodies was mapped and displayed on cross sections. Frontier production data were compared with sandstone development to better determine the influence of depositional facies on gas productivity.

CONTENTS

Figures

INTRODUCTION

In the Green River Basin of southwest Wyoming, the Frontier Formation comprises marine and nonmarine sandstone and shale facies, which record early Late Cretaceous foreland-basin sedimentation. Frontier shorelines, composed of wave-dominated deltaic headlands and delta-flank strandplains, prograded eastward into the western interior Cretaceous seaway (Myers, 1977; Winn and others, 1984; Moslow and Tillman, 1986, 1989) during Cenomanian and Turonian times (Merewether and others, 1984). The formation thickens and becomes increasingly more dominated by nonmarine facies westward into the Wyoming-Utah-Idaho Thrust Belt, whereas it thins and becomes increasingly more marine to the east. In the western part of the Green River Basin, both nonmarine (fluvial or distributary) channel-fill sandstone and marine shoreline sandstone are well developed in the Frontier and form important low-permeability gas reservoirs. Frontier sandstone reservoirs are enclosed in coastal-plain and nearshore-marine shale and sandy shale. Stratigraphy and depositional environment are important controls on reservoir geometry and quality in the Frontier.

The Frontier Formation is being studied in a program of investigations of low-permeability sandstones supported by the Gas Research Institute (GRI). This geologic research is just one aspect of a broad multidisciplinary program designed to increase knowledge and ultimate recovery of unconventional gas resources through integration of geology, log and core analysis, reservoir engineering, and hydraulic fracture modeling. The geologic investigations of the Frontier include studies of sandstone composition and diagenesis (Dutton, 1991), structural setting and natural fractures (Laubach, 1991), and stratigraphy and depositional environments (this study).

This report presents preliminary results of an ongoing study of Frontier stratigraphy and depositional environments along the Moxa Arch, which is the main area of Frontier gas production in the western Green River Basin. Drilling activity has provided abundant well log and core data for mapping and characterizing Frontier sandstone along the Moxa Arch. Previous studies on Frontier stratigraphy in this area (for example, McDonald, 1973; De Chadenedes, 1975; Myers, 1977; Moslow and Tillman, 1986) provided a starting point and context for this study, which extends their work by using more abundant and closely spaced well log and core data and by focusing on subsurface mapping on the La Barge Platform. Additionally, local Frontier geology is described for several wells (GRI cooperative wells and a staged field experiment well) for which extensive engineering, modeling, and log and core analysis data are publicly available through the GRI Tight Gas Sands Program. This study is still in progress, and the results presented here are preliminary. A final report describing the completed Frontier stratigraphic study will become available in early 1992.

The present report addresses (1) regional structural setting and stratigraphic framework, (2) depositional patterns and sandstone geometries on the La Barge Platform, and (3) depositional facies and reservoir development in the GRI cooperative wells. Potential stratigraphic and depositional controls on Frontier reservoir distribution and quality are discussed in each section.

METHODS

Logs from more than 800 wells and cores from 13 wells form the data base for subsurface geologic analysis of the Frontier Formation along the Moxa Arch (fig. 1). Most of the cores and about 500 of the logs are from wells on the La Barge Platform at the northern end of the arch. The La Barge Platform (also known as the Big Piney–La Barge area) is the largest Frontier gas-producing area in the basin and includes Hogsback, Tip Top, Chimney Butte, Fontenelle, and other important fields. GRI cooperative wells were completed in Fontenelle and South Hogsback fields on the La Barge Platform and in Church Buttes field near the southern end of the Moxa Arch (fig. 2). A GRI staged field experiment well (SFE No. 4) was completed in Chimney Butte field near the northeastern margin of the La Barge Platform (fig. 1). The

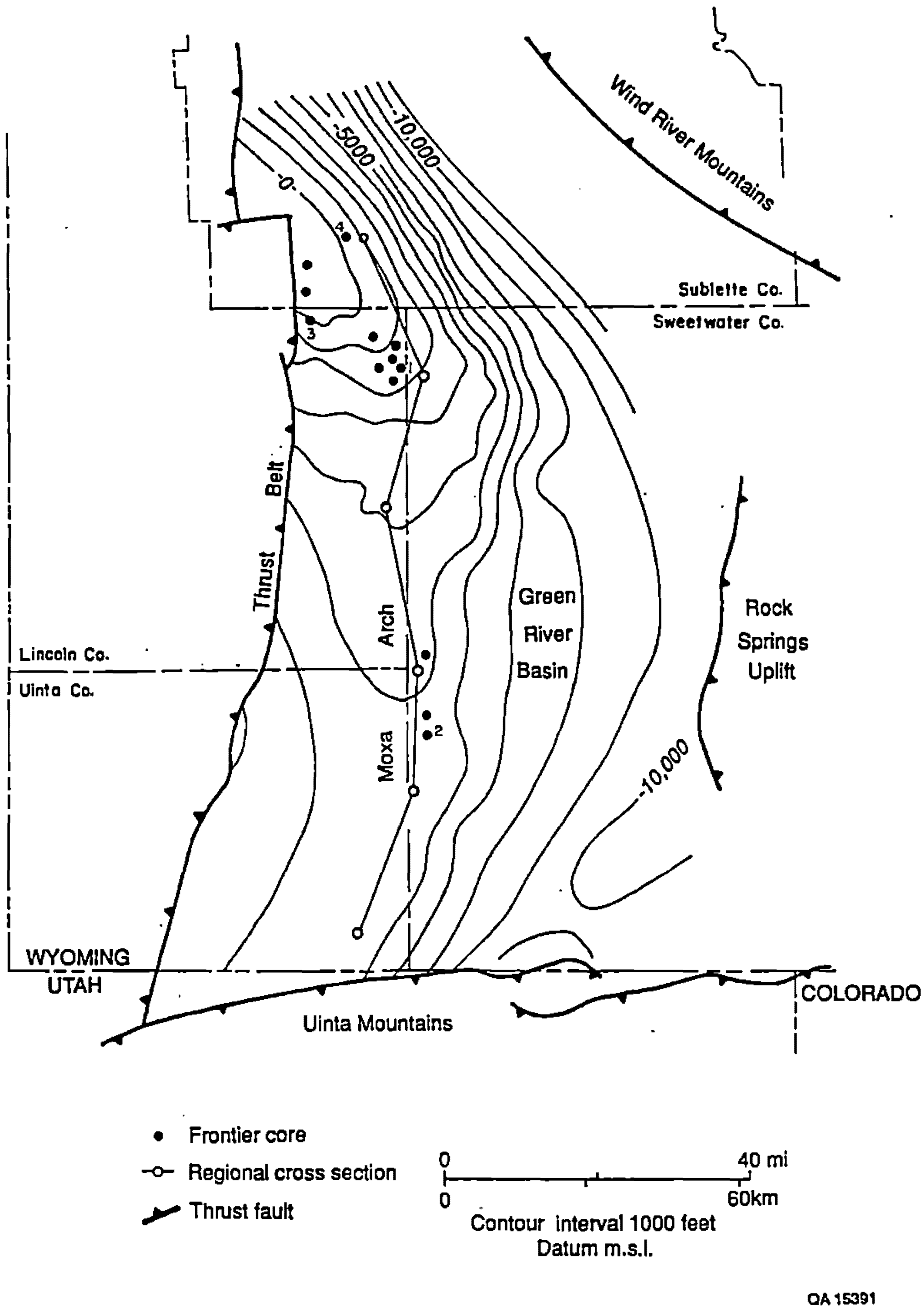

Figure 1. Structure-contour map on the top of the Second Frontier, showing major structural elements of the western Green River Basin (from Dutton and Hamlin, 1991). Location of wells from which Frontier cores were collected for this study is also shown. Wells discussed in text are (1) Terra Resources Anderson Canyon No. 3-17, (2) Wexpro Church Buttes Unit No. 48, (3) Enron South Hogsback No. 13-8A, and (4) S. A. Holditch & Associates SFE No. 4-24.

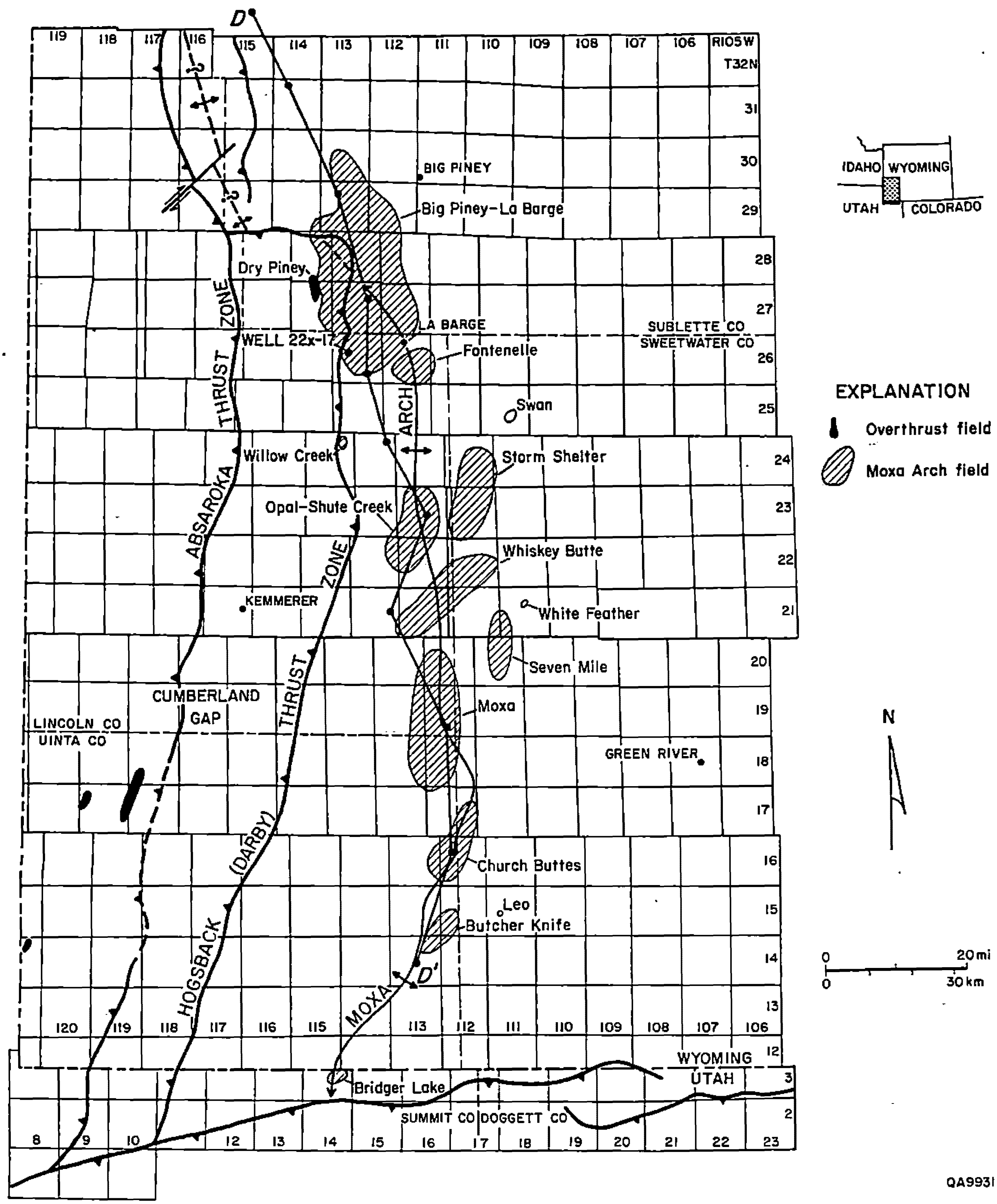

Figure 2. Map of major Frontier fields associated with the Moxa Arch, western Green River Basin (from Baumgardner and others, 1988; modified from Wach, 1977, his fig. 1). The Big Piney–La Barge area at the north end of the Moxa Arch is commonly referred to as the La Barge Platform in this report.

cooperative wells and SFE No. 4 provided complete log suites and continuous cores through the main Frontier sandstone intervals. Additional cores and many well logs used in this study were made available by operators. Other logs were purchased from commercial sources.

Correlation and interpretation of gamma-ray, resistivity, and spontaneous potential (SP) logs established the stratigraphic framework of the Frontier at regional and local scales. A series of generally continuous horizons in marine shale facies were correlated throughout the Moxa Arch study area. Although of undetermined origin, these correlation horizons are recognized by distinctive resistivity and gamma-ray signatures. These horizons are interbedded with the Frontier sandstone-bearing intervals and help establish the equivalency and continuity of individual sandstone bodies.

Cores were used for depositional facies interpretations and lithologic calibration of well logs. Detailed descriptions of lithologies, sedimentary structures and textures, grain sizes, and accessory components were made for each core. Facies interpretations, such as fluvial channel or marine shoreface, were based on core descriptions in the context of the regional depositional systems framework. Lithologies were compared with gamma-ray, resistivity, and SP log responses to establish cutoffs for determining sandstone thicknesses using logs from the many wells for which core was unavailable. These thickness values were then used to map the distribution and geometries of Frontier reservoir sandstones. A more limited data base of porosity (density, neutron, acoustic) logs was also used for sandstone mapping.

Frontier gas production data for wells along the Moxa Arch were compiled by the Geologic Survey of Wyoming (WGS) as a part of this project. The WGS collected data on initial potential, completion date, and cumulative production for most of the wells in the well log data base on the La Barge Platform. Production data from wells perforated in the Second Bench of the Second Frontier were mapped and compared with sandstone development to better determine the influence of geologic parameters, such as sandstone shaliness and depositional facies, on gas productivity.

REGIONAL GEOLOGIC FRAMEWORK

Structural Setting

The Green River Basin is part of the Rocky Mountain foreland region, an extensive foreland basin that has been segmented by Laramide uplifts. Foreland basins are elongate asymmetric troughs that commonly occur on the cratonic side of thrust belts. In a foreland basin strata thicken and dips steepen toward the thrust belt. Thrust loading causes the thickest sediment accumulations to be nearest the thrust front. Since the thrust belt also forms the sediment source area, foreland basins typically fill with thick, dominantly nonmarine strata that thin and become more marine-dominated down depositional dip (away from the thrust front). The Frontier Formation conforms to this structurally related depositional pattern. The present form of the Green River Basin resulted from folding and faulting during the Late Cretaceous–early Tertiary Laramide orogeny. Basement-cored Laramide uplifts, such as the Wind River and Uinta Mountains, form prominent basin boundaries (fig. 1). The Thrust Belt, which bounds the Green River Basin to the west, is a region of north-trending folds and thin-skinned, imbricate thrust faults that dip gently westward (fig. 3). Thrust movement occurred from the latest Jurassic to the early Eocene (Wiltschko and Dorr, 1983).

A major structure within the Green River Basin is the Moxa Arch, a broad north-trending uplift near the eastern margin of the Thrust Belt (fig. 1). Major uplift of the Moxa Arch apparently occurred during the Late Cretaceous (Wach, 1977). Uplift largely postdated Frontier deposition, but stratigraphic thinning indicates that some uplift was occurring along the southern part of the Moxa Arch during Frontier deposition (Thomaidis, 1973; Wach, 1977). The present attitude of the Moxa Arch indicates that more recent uplift has been concentrated in the north and has resulted in a southward tilt (fig. 1). Depth to the Frontier Formation increases from north to south along the Moxa Arch, ranging from about 6,000 ft to 15,000 ft below ground surface. The northern segment of the Moxa Arch, which trends northwest and

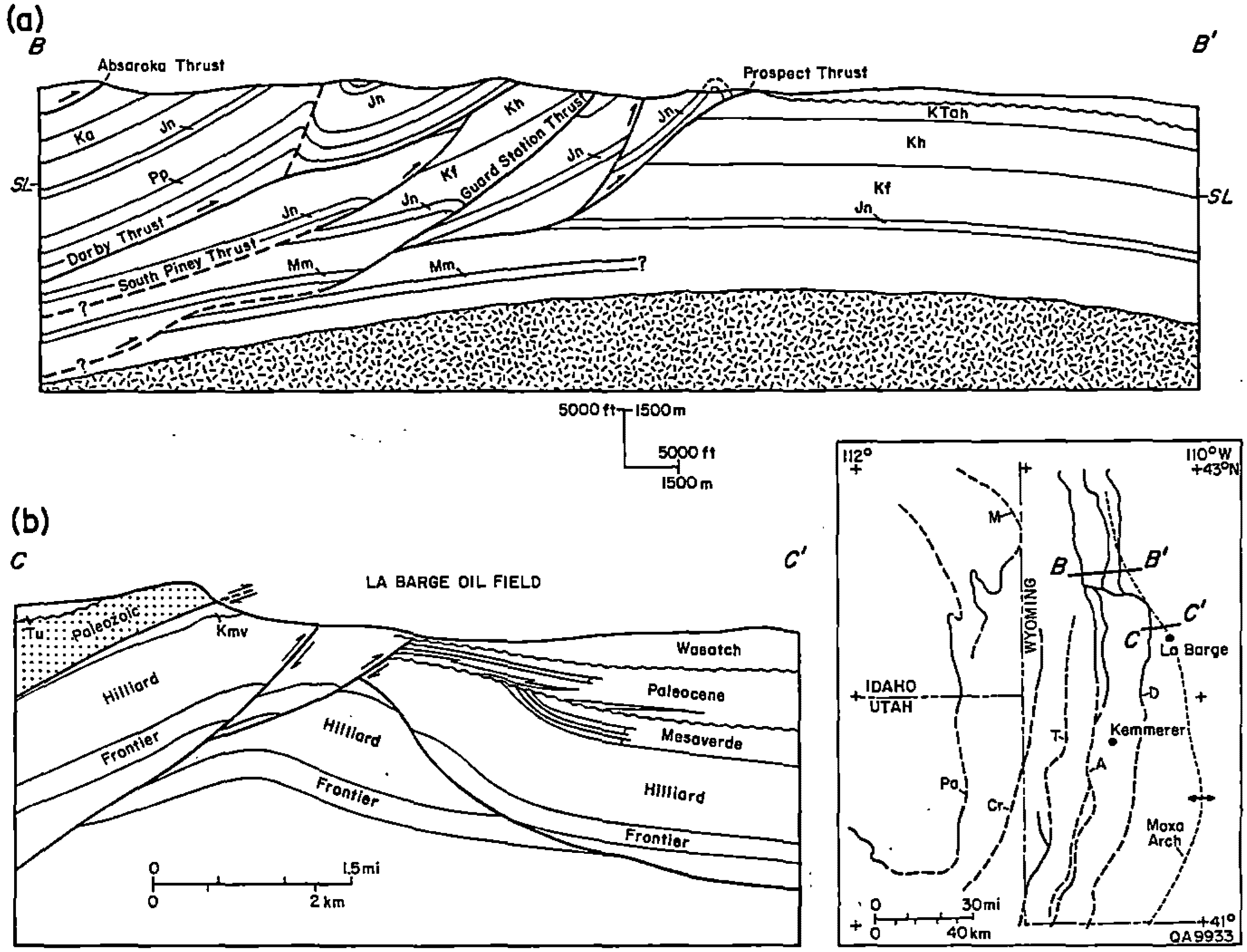

Figure 3. West-east structural cross sections across Thrust Belt, Moxa Arch, and La Barge Platform. From Wiltschko and Eastman (1983, their fig. 8). Symbols: KTah=Hoback and Adaville Formations, undivided; Kmv=Mesaverde Group; Kh=Hilliard Shale; Kf=Frontier Formation; Ka= Aspen (Mowry) Shale; Jn=Nugget Sandstone; Pp=Phosphoria Formation; Mm=Madison Limestone. See inset for location of cross sections. Symbols on inset: A=Absaroka Thrust; Cr=Crawford Thrust; D=Darby Thrust; M=Meade Thrust; Pa=Paris Thrust; T=Tunp Thrust. Frontier gas fields along the margin of the Thrust Belt, such as Tip Top and Hogsback, occur in structural settings similar to that in (b).

intersects the Thrust Belt (fig. 1), is called the La Barge Platform (fig. 2). The La Barge Platform encompasses some Frontier gas fields along the margin of the Thrust Belt, such as Tip Top and Hogsback, that are structurally complex (fig. 3). Most of the Frontier gas fields along the Moxa Arch, however, consist of simple unfaulted anticlines or mixed structural/stratigraphic traps (McDonald, 1973).

Stratigraphy

The Frontier Formation along the Moxa Arch contains marine shoreline sandstone and nonmarine fluvial channel-fill sandstone enclosed in thick, regionally extensive marine shales. Overlying the Frontier, the Hilliard (or Baxter) Shale is 2,000 to 3,000 ft thick and extends throughout the Green River Basin. The Hilliard Shale is chronostratigraphically equivalent in part to the Mancos Shale in Utah and Colorado (Molenaar and Wilson, 1990); the Hilliard/Mancos interval records a time of widespread marine shelf conditions in the Rocky Mountain foreland region. Underlying the Frontier is the Mowry (or Aspen) Shale, which also records a time of widespread marine shelf deposition. The Mowry Shale (uppermost Lower Cretaceous) is only 200 to 300 ft thick but extends throughout Wyoming and parts of adjacent states (Byers and Larson, 1979). Both the Hilliard Shale and the Mowry Shale include some sandstone in the Thrust Belt to the west. Hilliard sandstones produce gas locally in fields along the intersection between the La Barge Platform and the Thrust Belt.

The uppermost sandstone in the Frontier Formation is the First Frontier (fig. 4), a distal deltaic to nearshore marine sandstone that occurs only on the La Barge Platform (McDonald, 1973; De Chadenedes, 1975). First Frontier sandstone and sandstones in the overlying Hilliard Shale are similar in well log expression, stratigraphic position, and geographic distribution. First Frontier sandstone is separated from underlying Frontier sandstones by several hundred feet of regionally continuous marine shale (fig. 4).

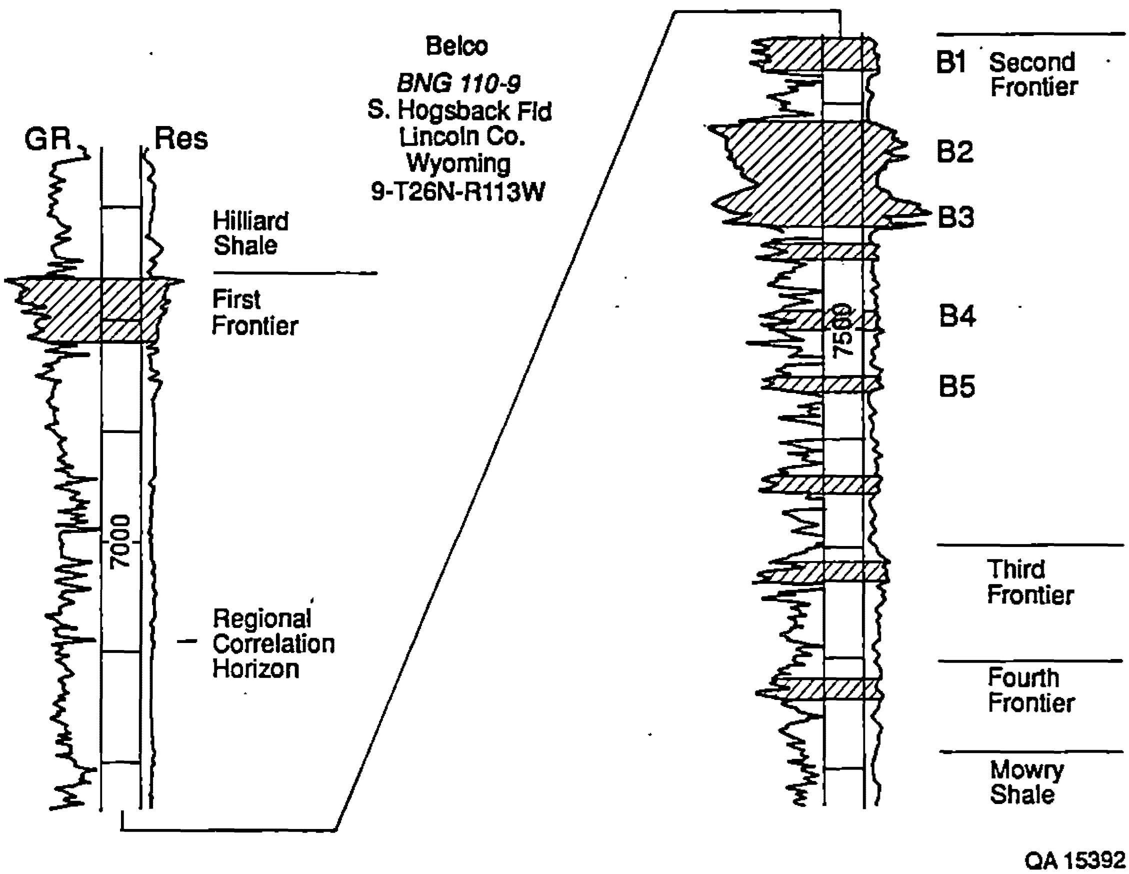

Figure 4. Typical gamma-ray/resistivity log, Frontier Formation, north Moxa Arch (from Dutton and Hamlin, 1991). Frontier sandstones are shaded.

Second Frontier sandstone extends the length of the Moxa Arch (fig. 5) and contains the most prolific Frontier gas reservoirs in the western Green River Basin. The Second Frontier is composed of several sandstone "benches" interbedded with shale (fig. 4). The First, Fourth, and Fifth Benches are laterally discontinuous fluvial channel-fill sandstones, whereas the Second Bench is a marine shoreline sandstone having widespread continuity. The Third Bench is a shoreline sandstone that underlies and merges with the Second Bench in the western part of the La Barge Platform. Nonmarine organic-rich shales, thin coal beds, and bentonites (altered volcanic ash) are associated with the fluvial channel-fill sandstones, whereas bioturbated marine shale and sandy shale commonly bound Second Bench shoreline sandstone.

The Second Frontier thins southward along the Moxa Arch, owing mainly to erosional truncation (fig. 5). On the La Barge Platform in the north, the First Bench includes erosionally based fluvial channel-fill sandstone, which is typically separated from the underlying Second Bench shoreline sandstone by 5 to 20 ft of transitional, fine-grained facies (bay/lagoon, swamp, marsh). In fields along the middle and southern parts of the arch, such as Whiskey Butte and Church Buttes (fig. 2), erosional downcutting by First Bench channels generally removed the transitional shale and variable amounts of the underlying Second Bench shoreline sandstone (fig. 5). Whereas Second Bench shoreline sandstone forms the most important reservoirs in the north, First Bench fluvial channel-fill sandstone forms the most important reservoirs in the south (Moslow and Tillman, 1986, 1989). The Fourth and Fifth Benches of the Second Frontier also disappear southward along the arch, apparently owing to a combination of stratigraphic pinch-out and erosional truncation. Fourth and Fifth Bench fluvial channel-fill sandstones form reservoirs locally, but only on the La Barge Platform.

The Second Frontier formed in an eastward-prograding fluvial-deltaic depositional system, in which the reservoir sandstone facies are primarily fluvial channel-fill and marine shoreline (strandplain). Sandstone thickness in the Second Frontier generally decreases to the east and south (fig. 6), owing in part to total interval thinning in those directions. Net thickness of sandstone is greatest in northeast Lincoln County and northwest Sweetwater County (fig. 6),

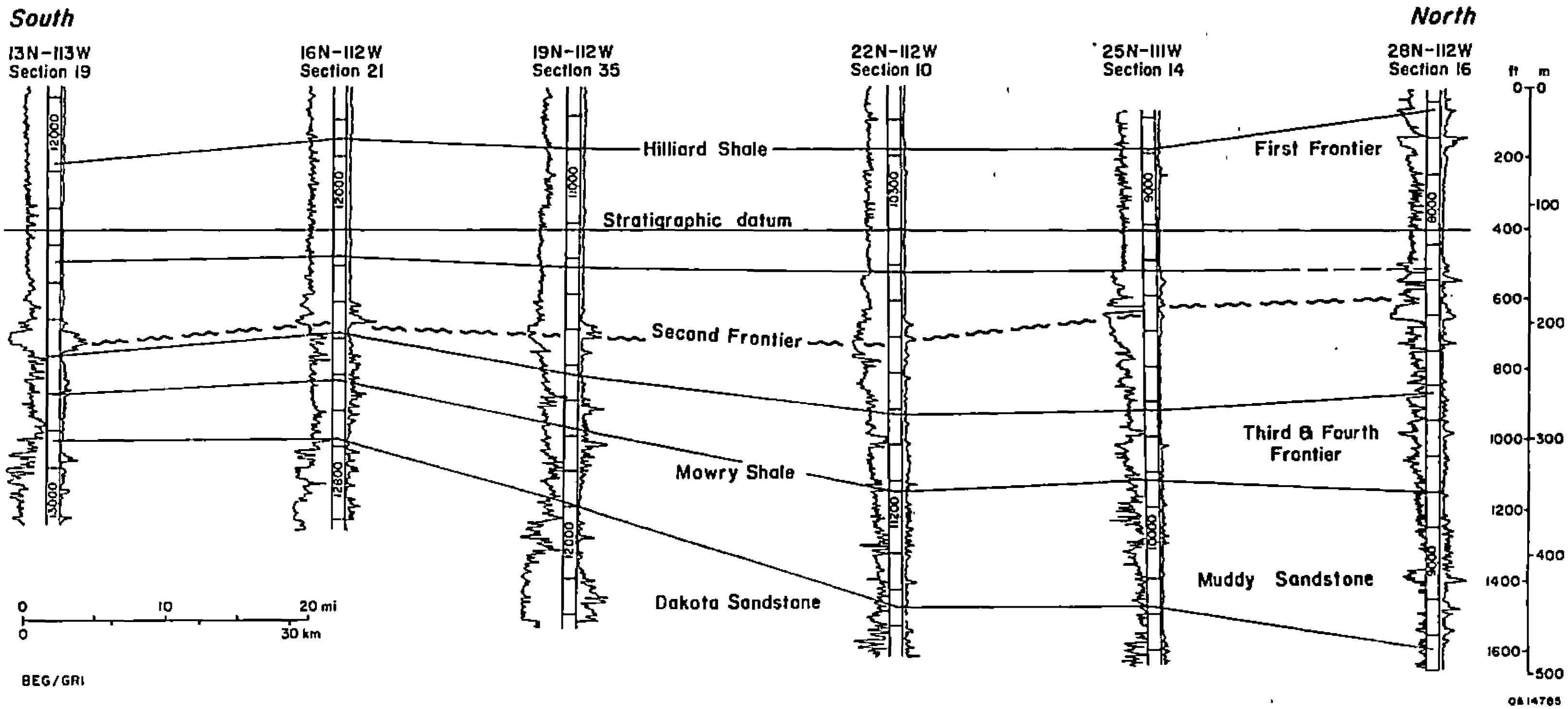

Figure 5. Regional north-south, gamma-ray/resistivity cross section along the Moxa Arch (modified from Dutton and Hamlin, 1991). Line of section shown in figure 1. An erosional unconformity (dashed wavy line) within the Second Frontier separates First Bench fluvial channel-fill sandstone from underlying Second Bench marine shoreline sandstone. A transgressive surface of erosion occurs at the base of the Second Bench (see fig. 10). Other (straight) lines shown on this section are correlation-based chronostratigraphic horizons. Formation boundaries (lithostratigraphic) are not shown.

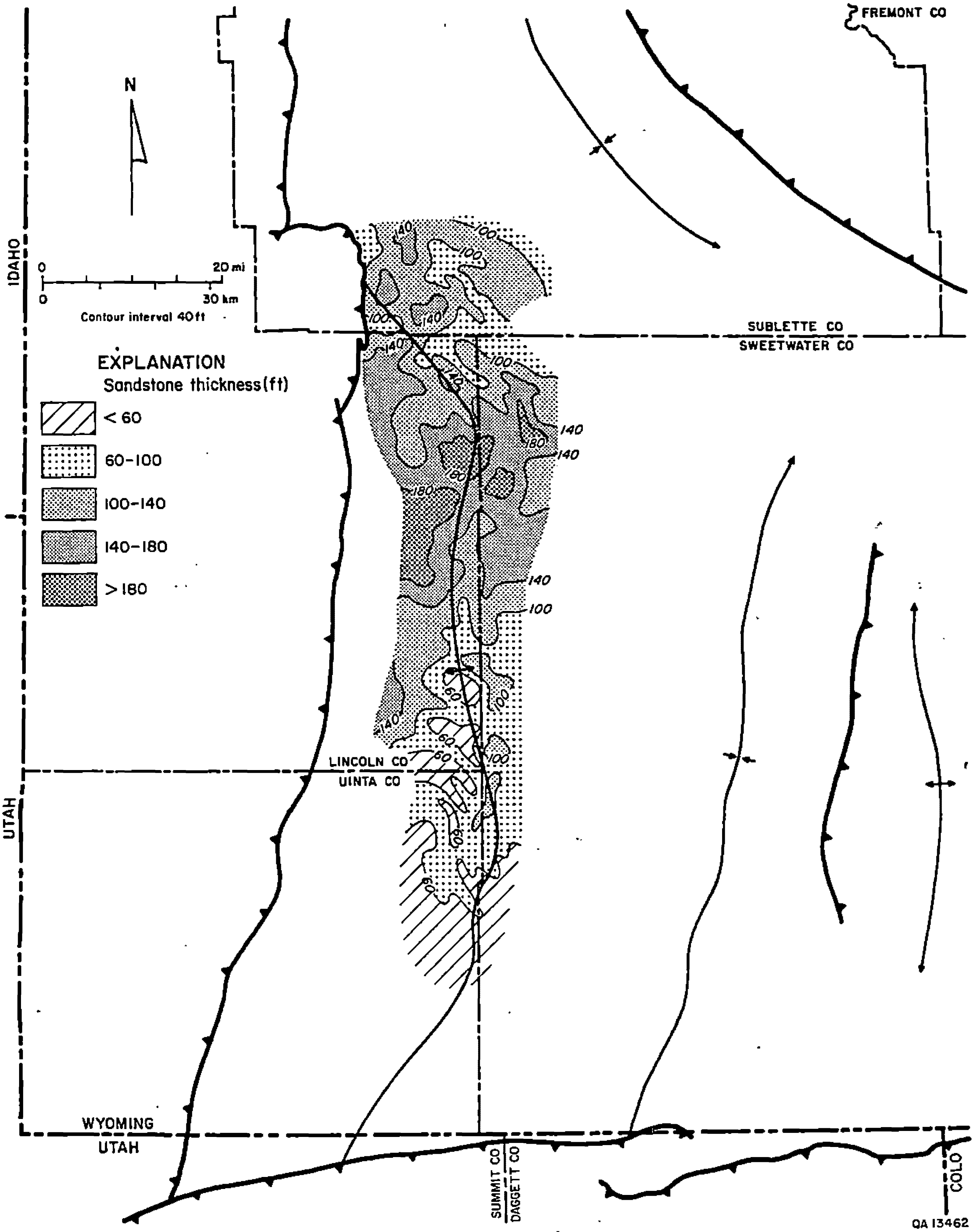

Figure 6. Map showing thickness of sandstone in the Second Frontier along the Moxa Arch. Several sandstone bodies (the benches) are combined on this map.

delineating a major deltaic depocenter in the Frontier along this part of the western interior Cretaceous seaway. The map of Second Frontier sandstone thickness (fig. 6) includes multiple sandstone bodies of varying origins, so that facies-related trends are not clearly displayed. Nevertheless, southeast-trending contours along the southern Moxa Arch reflect the dominance of dip-oriented fluvial channel-fill sandstones, and crudely developed northeasterly trends in the north suggest the presence of thick strike-aligned marine shoreline sandstone (fig. 6). Previous studies (McDonald, 1973; Moslow and Tillman, 1989), as well as more detailed sandstone mapping (to be discussed), confirm that Second Frontier shorelines trended generally northeast.

On the La Barge Platform, the Second Frontier is underlain by interbedded marine shales and shoreline sandstones known as the Third and Fourth Frontier (fig. 4). Sandstones are generally thin and laterally discontinuous in the Third and Fourth Frontier intervals, which are transitional with the underlying Mowry Shale. Southward along the Moxa Arch, the Third and Fourth Frontier intervals thin and become shalier, essentially grading into the upper part of the Mowry Shale (fig. 5).

SECOND FRONTIER SANDSTONE ON THE LA BARGE PLATFORM

Sandstone Depositional Patterns

Second Frontier sandstone bodies display geometries and trends inherited from the depositional environment but modified by shoreline progradation and variable subsidence. On the La Barge Platform, the Second and Third Benches together form a continuous, northeast-thinning sheet of sandstone (fig. 7). It is difficult to distinguish the Second Bench from the Third Bench using well logs alone, and since they were deposited in similar environments, they will be discussed as a single unit, which to follow common usage will be termed "Second Bench." Studies of core indicate that the Second Bench was deposited in a marine shoreline environment comprising lower shoreface (below wave base) shaly sandstone and upper

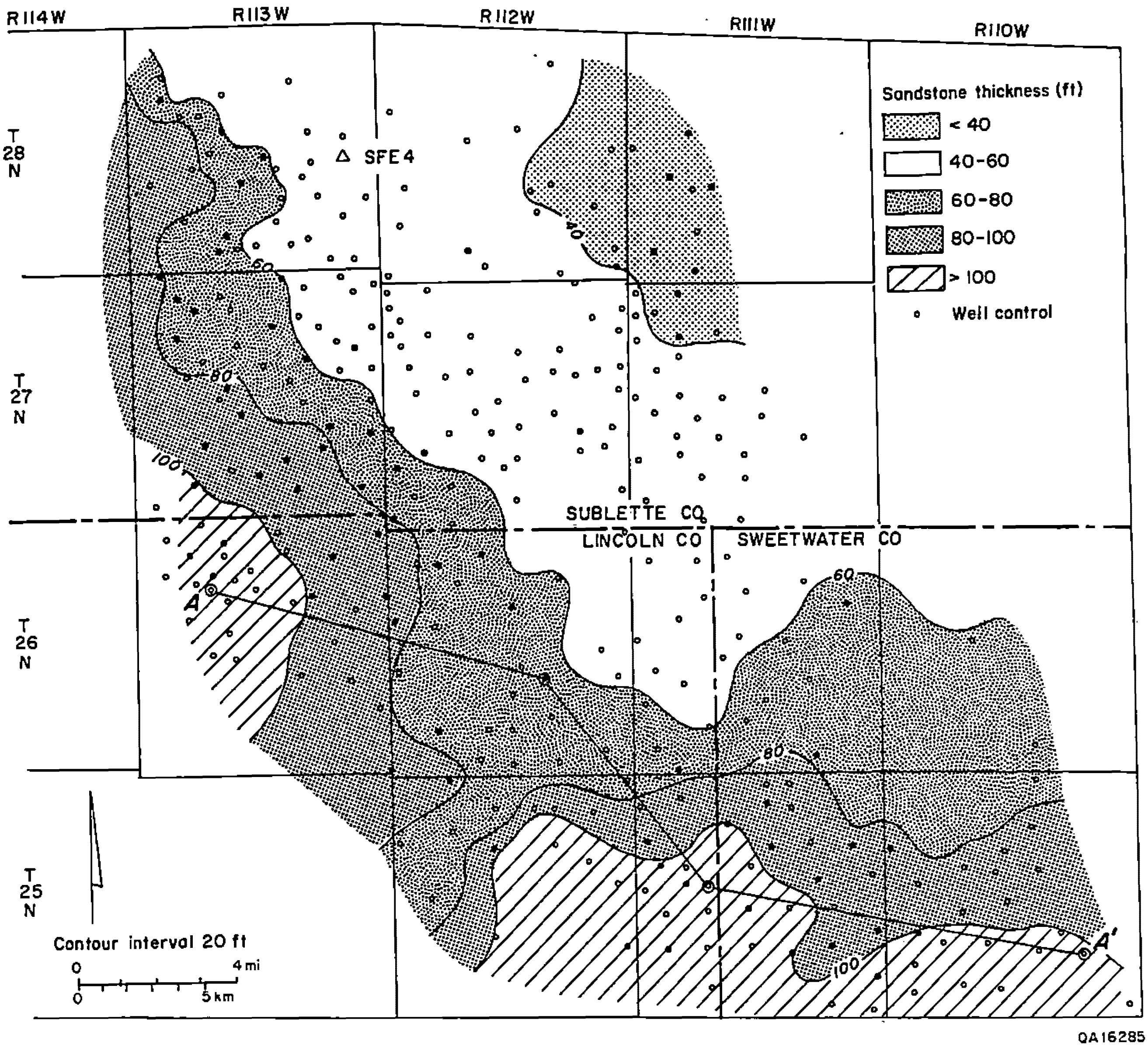

Figure 7. Map showing thickness of sandstone in the Second and Third Benches of the Second Frontier on the La Barge Platform. The Second and Third Benches merge across much of this area.

shoreface (above wave base) clean sandstone. The sandy shoreface was probably only about 1 mi wide but built seaward (prograded) through time by longshore sand transport and deposition. Sediment was supplied to the shoreline by rivers and reworked along the shoreface by wind- and wave-driven currents. Shoreline progradation constructed a laterally continuous sheet of sandstone composed of amalgamated shoreface sequences (fig. 8). Although the dominant Second Bench shoreline trend was probably northeast, differential subsidence during deposition apparently is responsible for southwestward-increasing sandstone thickness (fig. 7).

The First Bench of the Second Frontier was deposited on a lower coastal plain (delta plain) and includes discontinuous fluvial channel-fill sandstone bodies. Southeast-trending belts of sandstone (fig. 9) delineate the positions on the coastal plain occupied by river channels. Through time the channels migrated laterally or changed course abruptly, resulting in the preservation of a network of lenticular sandstone bodies (fig. 9). During floods overbank flow spread sand across the coastal plain, causing the First Bench to contain at least some thin sandstone in most wells. Thicker, more lobate First Bench sandstone near the southeastern margin of the La Barge Platform reflects deposition in a deltaic shoreline environment.

Second Frontier stratigraphy and sandstone development in the vertical dimension are well displayed on a well log cross section (fig. 10). The Fourth and Fifth Benches of the Second Frontier together comprise a heterogeneous zone of fluvial channel-fill sandstones, nonmarine and transitional-marine shales, and volcanic ash deposits. This zone apparently becomes more marine down depositional dip (southeast). Semicontinuous volcanic ash deposits (bentonites), identified by high gamma-ray spikes, form chronostratigraphic horizons useful for dividing the Fourth and Fifth Benches (fig. 10). The upper boundary of the Fourth Bench is a transgressive surface of erosion, recording a time when relative sea level rose and the shoreline encroached on the coastal plain. Marine facies abruptly overlying nonmarine facies characterize this surface in core. Shoreface erosion apparently truncated the upper part of the Fourth Bench to the southeast (fig. 10).

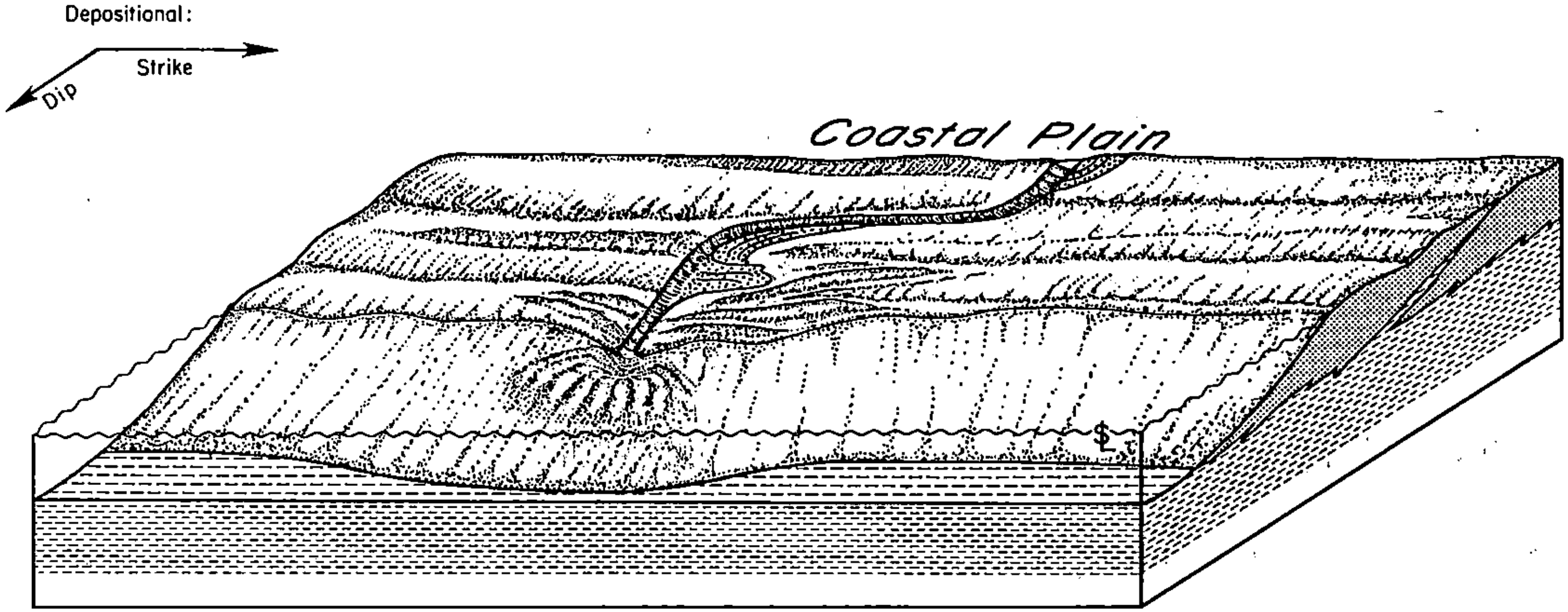

Figure 8. Depositional model of a sand-rich strandplain (from Galloway and Cheng, 1985). Closely offlapping shoreface sandstone wedges (stippled) amalgamate into a continuous sheetlike sandstone body, which is compartmentalized internally by thin shale layers along relict depositional surfaces and by facies changes.

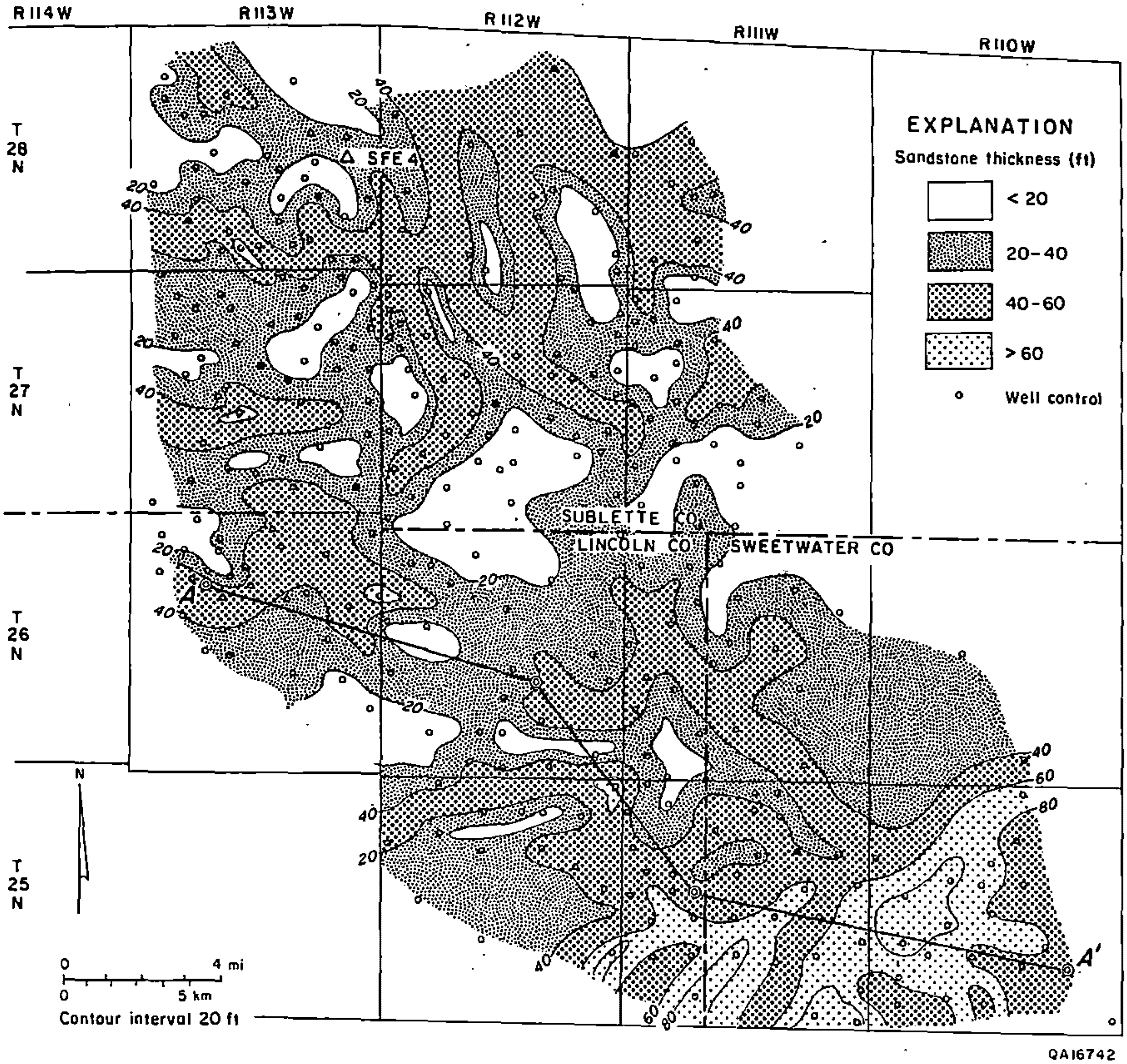

Figure 9. Map showing thickness of sandstone in the First Bench of the Second Frontier on the La Barge Platform.

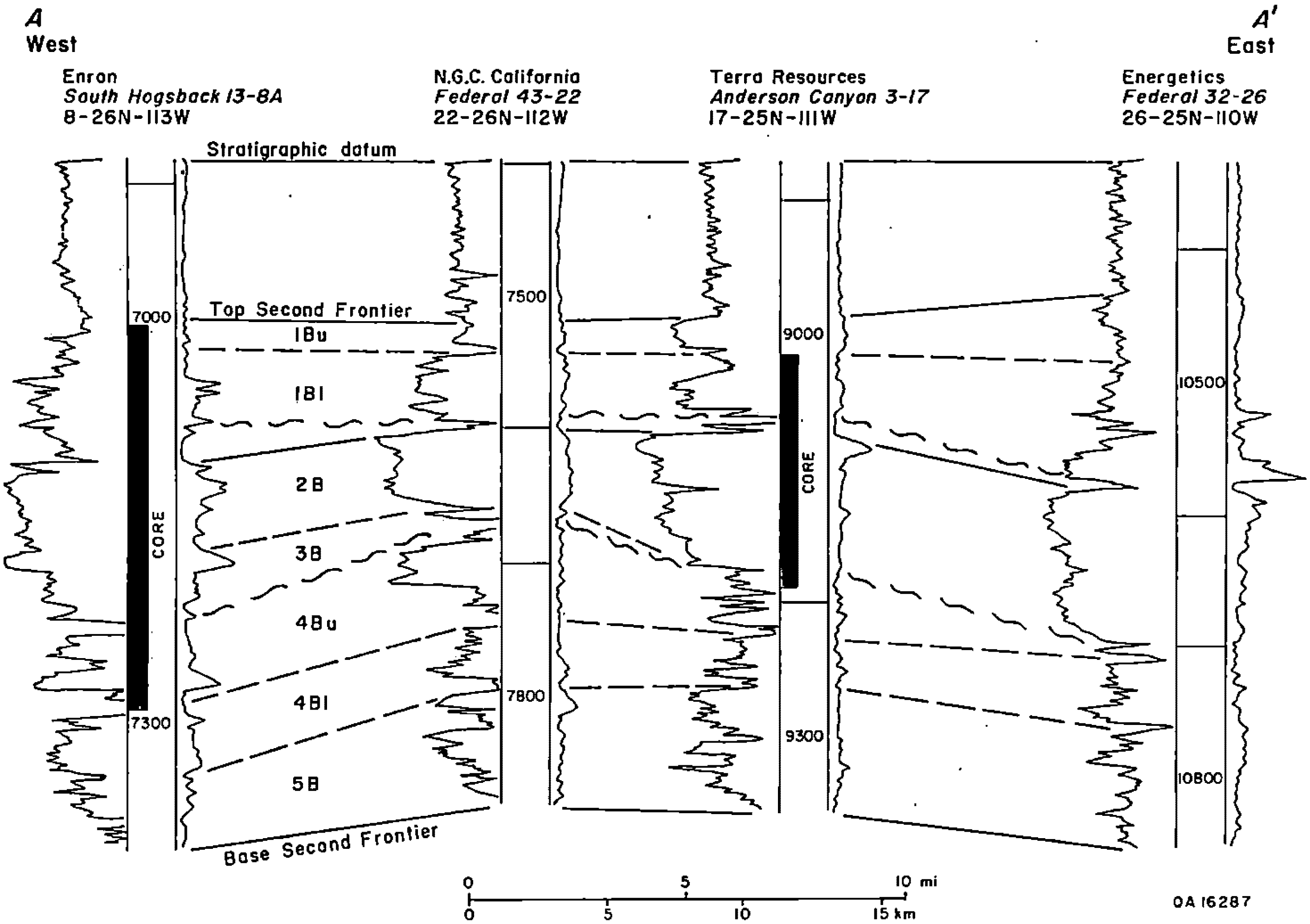

Figure 10. West-east gamma-ray/resistivity cross section of the Second Frontier on the La Barge Platform. Line of section shown in figure 7. Cored intervals in two GRI cooperative wells are also shown. The straight lines are correlation horizons, and the wavy lines represent unconformities (dashed where approximately located).

After the sea had completely transgressed the La Barge Platform, renewed sediment input and shoreline progradation constructed the Second and Third Benches. The lateral continuity of sandstone in this interval resulted from seaward building of the shoreface at a rate sufficient to keep pace with subsidence. This process created a sheetlike geometry that is superficially homogeneous but is actually compartmentalized internally by facies boundaries and depositional surfaces (fig. 8). In individual wells the Second Bench commonly forms a single progradational shoreline sequence: lower shoreface shaly sandstone overlain by upper shoreface clean sandstone. Gradational "upward cleaning" is reflected in upwardly decreasing gamma-ray response and upwardly increasing resistivity. The Third Bench forms a poorly defined upward cleaning sequence, which apparently pinches out toward the east (fig. 10).

The First Bench is separated from the Second Bench by a widespread high gamma-ray/low resistivity shale (fig. 10). Origin of this shale is problematic. In core it appears to be composed of depositional facies, such as bay/lagoon or coastal marsh, that are transitional between the marine Second Bench and the nonmarine First Bench. Its widespread distribution, however, suggests that this shale may actually record a relative sea-level rise and partial flooding of the coastal plain. The First Bench is a heterogeneous zone of primarily nonmarine facies, which is similar to the Fourth and Fifth Benches. Fluvial channel-fill sandstone is best developed in the lower part of the First Bench, where it generally causes blocky to upward increasing gamma-ray responses (fig. 10). The upper part of the First Bench forms an eastward thickening zone that is transitional into the overlying, regionally extensive marine shale. Sandstone of probable shoreface origin occurs in the upper First Bench in the southeast part of the La Barge Platform (fig. 10).

Clean Sandstone Distribution

Studies of core show that the clay content of Frontier reservoirs influences porosity and permeability. Frontier pay zones commonly lie in sandstones having low detrital clay contents, although framework grain composition and postdepositional diagenesis severely limit reservoir quality even in clean Frontier sandstone (Dutton, 1991). Therefore, net clean sandstone does not necessarily equal net pay, but distinguishing low-clay (clean) sandstone from clay-rich (shaly) sandstone is an important first step in determining the distribution of potential Frontier reservoirs. By comparing core properties with corresponding log responses, gamma-ray and resistivity cutoffs were established for measuring thicknesses of clean sandstone (sandstone having less than about 10 percent clay content). Neutron/density logs, where available, aided clean sandstone determination. Other variables besides clay content influence well log responses, so that core-calibrated log measurements of clean sandstone are most accurate in limited areas where these other variables, such as connate water composition and formation mineralogy, are relatively constant. For more regional mapping, log cutoffs must be adjusted for varying local conditions. Net clean sandstone maps reveal depositional-facies-related trends, such as shorelines and channels, that can be extended into sparsely drilled areas and that outline areas having potentially favorable reservoir development.

The apparent distribution of clean sandstone in the Second Bench (fig. 11) is influenced by factors other than depositional processes. Increasing thickness of clean sandstone to the west is related in part to increased subsidence and thicker gross sandstone in that area (fig. 7). Carbonate cement and calcareous shell debris are more abundant in the western part of the La Barge Platform and cause high resistivity responses, which can lead to overestimation of clean sandstone thicknesses. Thus, figure 11 probably most accurately reflects clean sandstone distribution in the east half of the mapped area.

Within the Second Bench sheet sandstone, net clean sandstone displays distinct northeast trends (fig. 11). Clean sandstone in the Second Bench lies primarily in upper shoreface facies, which form in the inner part of the nearshore environment, where waves and vigorous currents strongly agitate the sediment, winnowing finer particles (silt and clay). In a progradational, wave-dominated delta and delta-flank strandplain system, foreshore and beach-ridge facies, also composed of clean sandstone, generally overlie the upper shoreface (Heward,

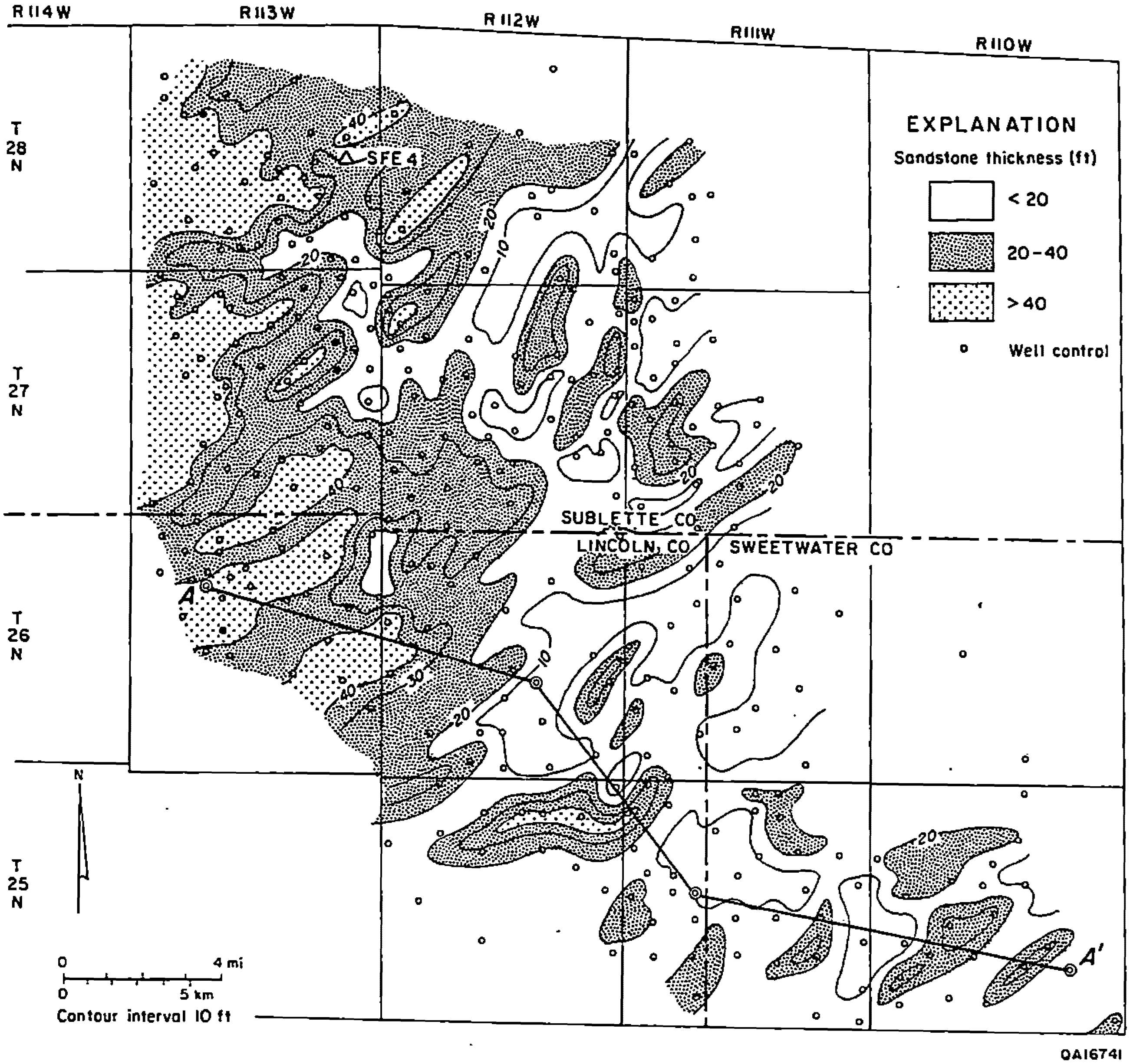

Figure 11. Net clean sandstone map of the Second Bench of the Second Frontier on the La Barge Platform.

1981) but apparently are poorly preserved in the Second Bench. Thus, the Second Bench clean sandstone map (fig. 11) is essentially a map of the thickness of upper shoreface facies, and the northeast trends probably delineate successive positions of the shoreline as it prograded seaward (southeast). The fact that northeast trends are not present in the gross thickness of Second Bench sandstone (fig. 7) is problematic, but apparently can be attributed to westward- and southwestward-increasing subsidence overwhelming the influence of depositional environment on sandstone thickness patterns.

In the First Bench, clean sandstone forms narrow southeast-trending belts (fig. 12), which are similar to but thinner than those seen on the map of First Bench gross sandstone (fig. 9). These sandstone belts record the positions of fluvial channels. First Bench rivers, however, did not supply sediment to Second Bench shorelines. First Bench shoreline facies occur mainly east and southeast of the Moxa Arch and postdate the Second Bench. Fluvial channel-fill facies in the Second Bench are located west of the Moxa Arch and were rarely observed in core from wells on the La Barge Platform.

On the La Barge Platform, the First and Second Benches of the Second Frontier contain most of the clean sandstone in the lower Frontier interval (fig. 13). The Fourth and Fifth Benches of the Second Frontier and the underlying Third Frontier and Fourth Frontier are more discontinuous and contain only isolated clean zones. The Third Frontier and the Fourth Frontier probably represent isolated shoreface sequences in a mud-dominated shoreline system. The Fourth and Fifth Benches are fluvial channel-fill deposits that formed on a mud-rich coastal plain having isolated fluvial channels. The First Bench, in contrast, formed on a relatively sand-rich coastal plain. First Bench fluvial channels migrated laterally, forming belts of sandstone that are several times wider than the original river channel and that are flanked by broad aprons of thinner sandstone (fig. 9), which were deposited by overbank flow during floods. First Bench clean sandstone is more limited and discontinuous (figs. 12 and 13), occurring primarily within thicker channel-fill facies. Clean sandstone is most continuous in the Second

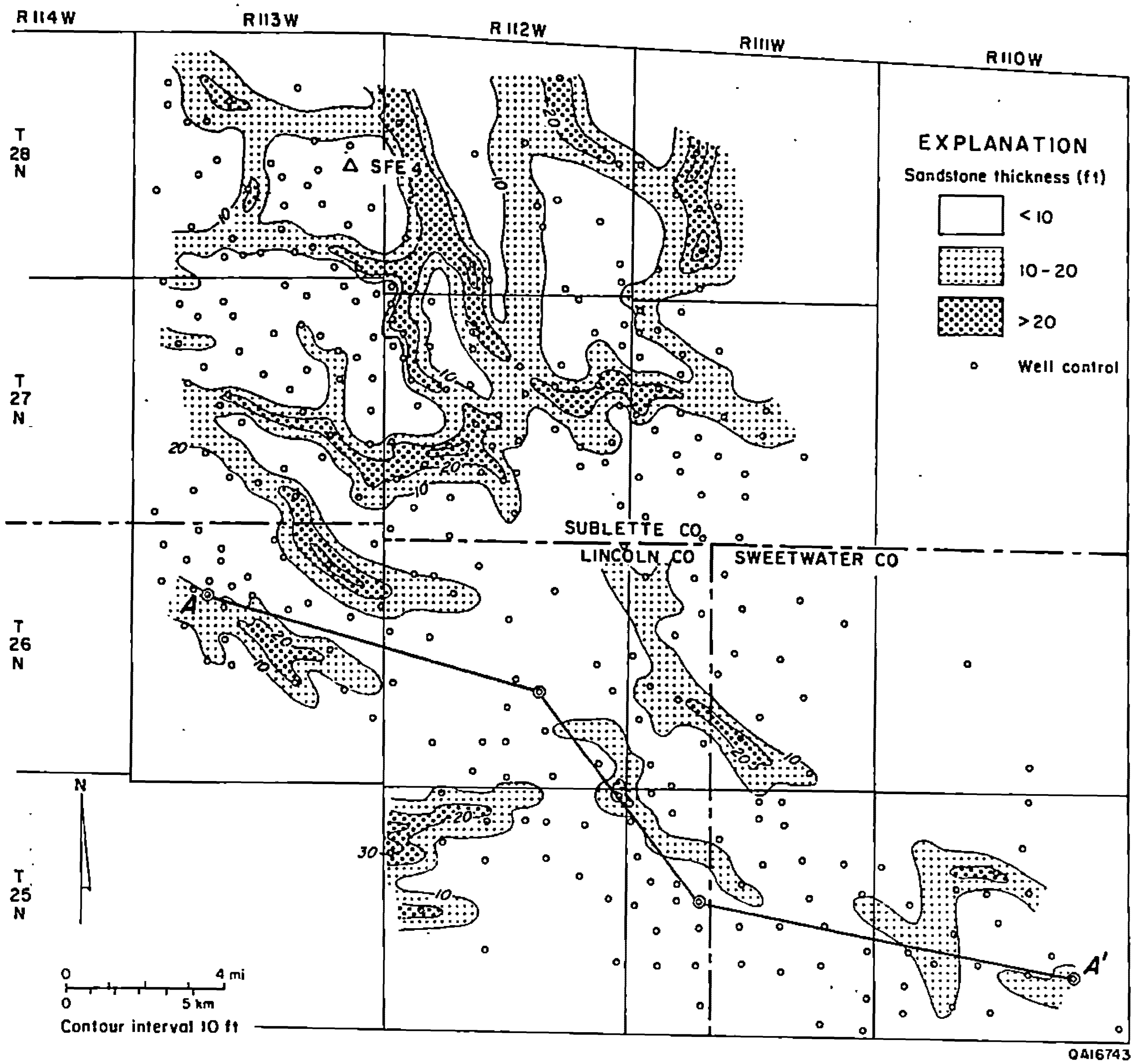

Figure 12. Net clean sandstone map of the First Bench of the Second Frontier on the La Barge Platform.

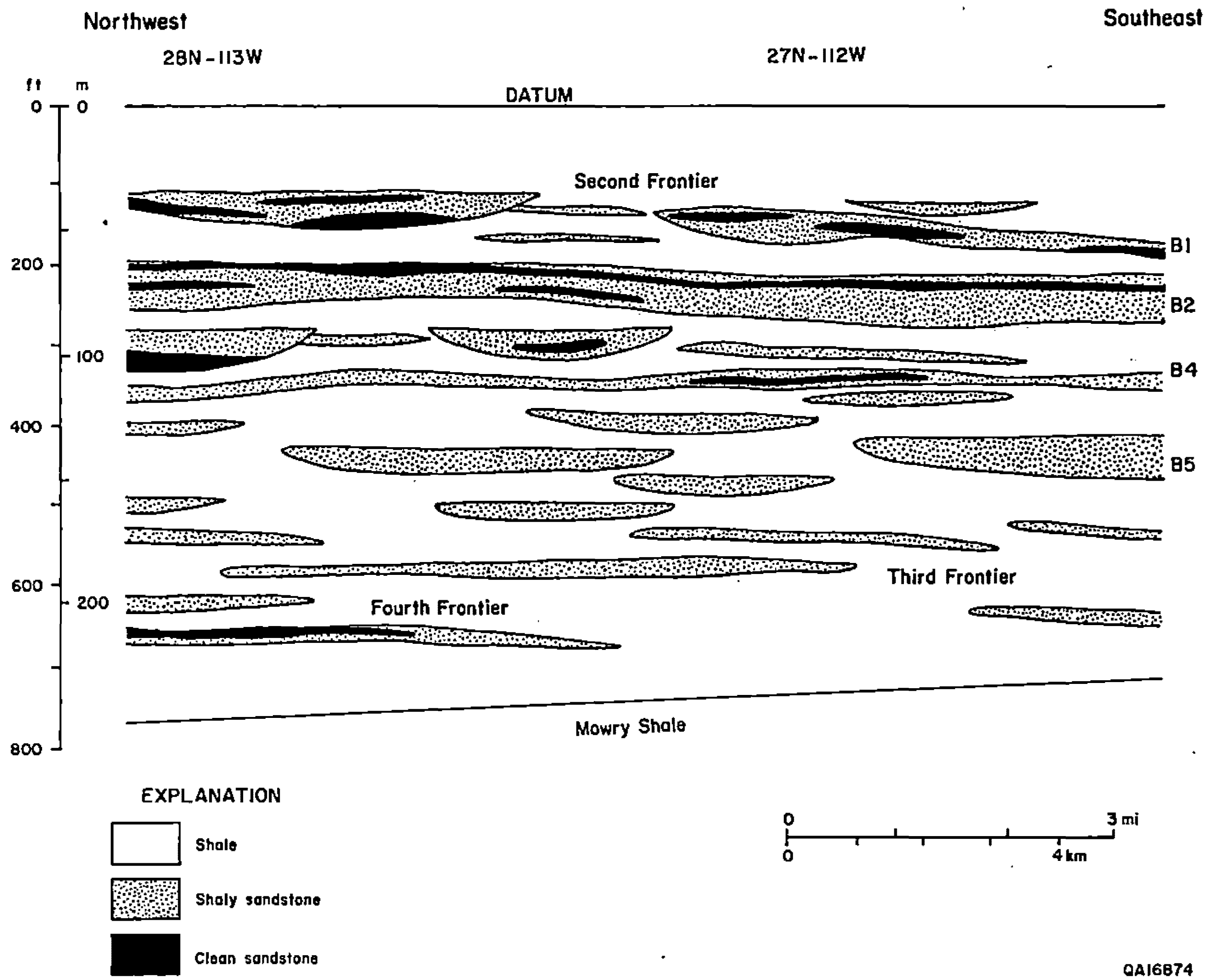

Figure 13. Northwest-southeast schematic cross section showing distribution of shaly sandstone and clean sandstone in the lower (Second, Third, and Fourth) Frontier interval, north La Barge Platform.

Bench (fig. 13), but even there its thickness is highly variable (fig. 11). Lateral continuity is characteristic of progradational shoreface sandstone sequences (Heward, 1981).

Sandstone Porosity Maps

In this study various types of sandstone maps were used to help determine the distribution and quality of Frontier reservoirs: clean sandstone maps using gamma-ray and resistivity logs were discussed previously, construction of qualitative permeability maps using SP logs are in progress, and porosity maps using density, neutron, and acoustic logs are discussed here. In Frontier sandstones, porosity determined from logs has a poor correlation with permeability determined from core analysis. Even the correlation between core-measured porosity and permeability is relatively low, and so porosity is not always a good predictor of permeability in Frontier sandstones (Dutton, 1991). However, porosity maps are useful, especially when compared with other types of maps, to help delineate potential reservoir rock.

Because the relationship between porosity and permeability in Frontier sandstone is poor, the cutoff used for measuring porosity thickness from logs was somewhat arbitrarily set at 15 percent. This value yielded thickness variations that were readily mappable. Additionally, this cutoff yielded results that are qualitatively valuable: log porosities are typically highest in areas where sandstone having at least 15 percent log porosity is thickest. To avoid significant shale effects, only clean sandstone and slightly shaly sandstone (clay volume less than approximately 20 percent) were included in porosity-thickness measurements.

In the northwest part of the La Barge Platform (Tip Top/Hogsback area), Second Bench sandstone having at least 15 percent log porosity displays thickness trends (fig. 14) that are similar in orientation although not always in location or magnitude to those on the clean sandstone map (fig. 11). Porosity in Frontier clean sandstone is commonly low, owing to postdepositional compaction and cementation. In slightly shaly sandstone, abundant microporosity may cause total porosity to be greater than 15 percent (Dutton, 1991). Thus, the

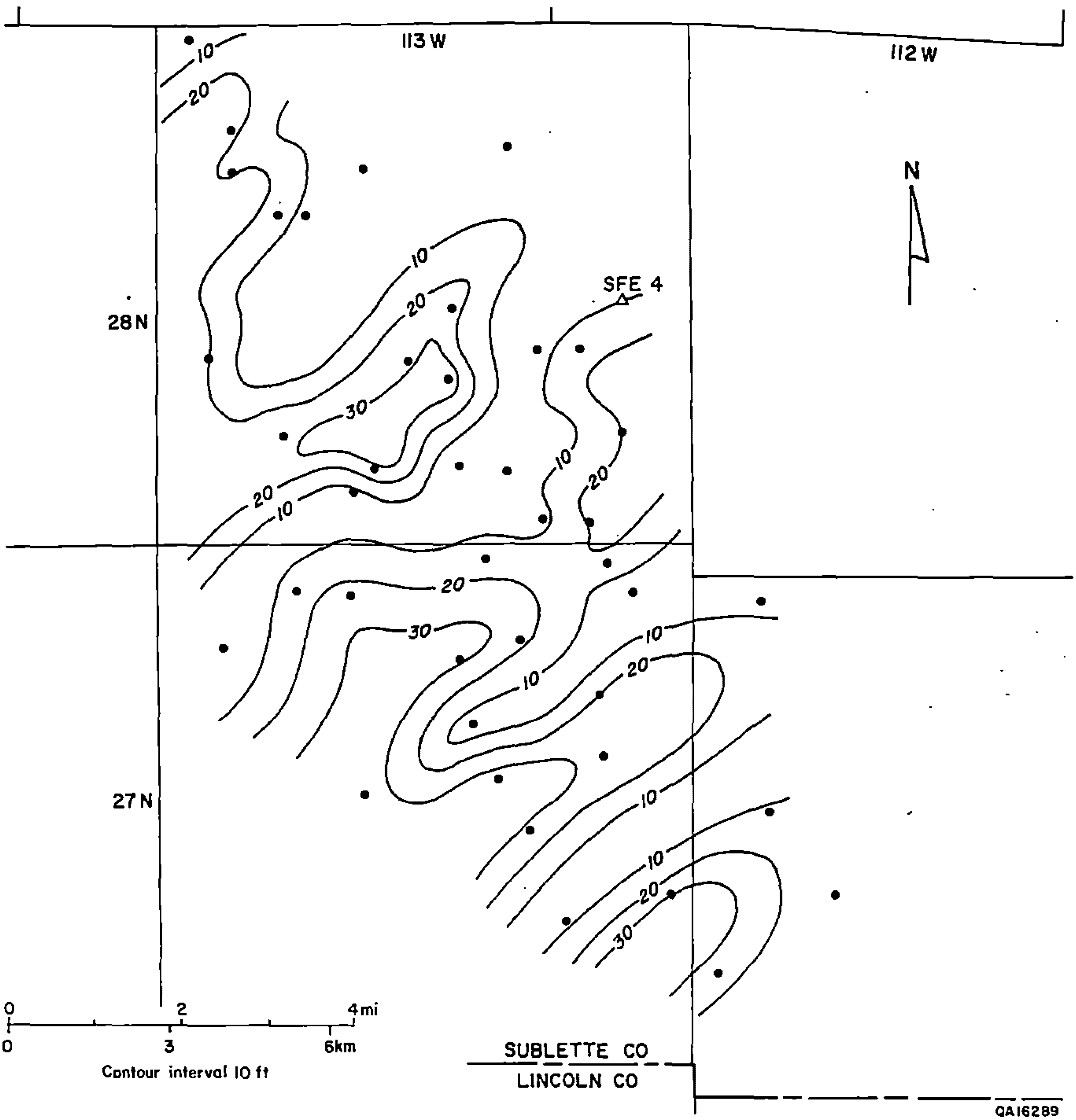

Figure 14. Map showing net thickness of Second Bench sandstone having at least 15 percent log porosity, northwest part of the La Barge Platform. Location of GRI research well, SFE No. 4, is also shown.

distribution of clean sandstone (fig. 11) does not precisely match that of porous sandstone (fig. 14), but permeability is likely to be highest in areas were the two coincide.

In the southeast part of the La Barge Platform (Fontenelle area), net porous Second Bench sandstone occurs in lobate bodies that display no clear trend (fig. 15) but that coincide approximately with areas having thick gross sandstone (fig. 7). In this area sandstone having at least 15 percent log porosity includes not only the clean upper shoreface facies but also much of the underlying, slightly shaly, lower shoreface facies. Core data indicate that Second Bench lower shoreface sandstone in the Fontenelle area commonly has 15 percent porosity but rarely has appreciable (stressed) permeability (0.009 md average). Of the maps illustrated here, the clean sandstone map (fig. 11) probably best indicates the distribution of permeable Second Bench sandstone in the southeast part of the La Barge Platform, although studies of core show that much of this clean sandstone has low permeability (less than 0.1 md).

Second Bench Production Trends

Second Bench production trends reflect sandstone depositional patterns, but other variables also influence well productivity, as illustrated by an initial potential map (fig. 16). Most Frontier wells on the La Barge Platform have perforations in the Second Bench, and although net pay zones there are typically much thinner, a rough correlation exists between well productivity (fig. 16) and gross sandstone thickness (fig. 7). Production trends (fig. 16) also show some coincidence with clean sandstone (fig. 11) and porous sandstone (fig. 14). Although the productive limits of the Second Bench may be more attributable to sandstone thinning and low permeability than to structural position (McDonald, 1973; Schultz and Lafollette, 1989), the distribution of wells having high initial potentials coincides roughly with the structurally highest part of the La Barge Platform. Permeabilities in many of the wells having high initial potentials apparently are anomalously high for Frontier sandstone, and sandstone maps based on SP logs reveal a correlation between high Second Bench initial potentials and large negative

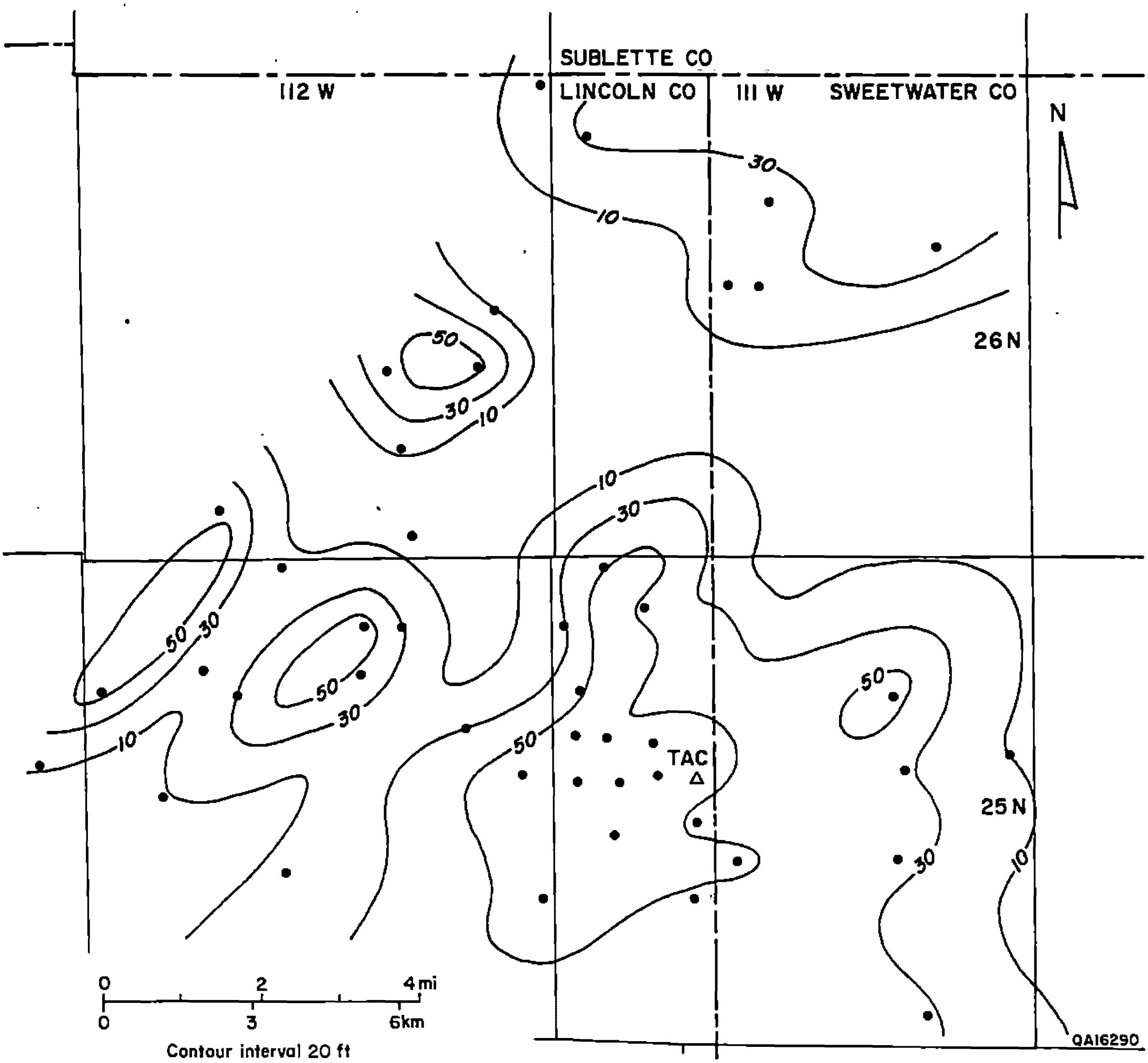

Figure 15. Map showing net thickness of Second Bench sandstone having at least 15 percent log porosity, southeast part of the La Barge Platform. Location of Terra Anderson Canyon No. 3-17 well (TAC) is also shown.

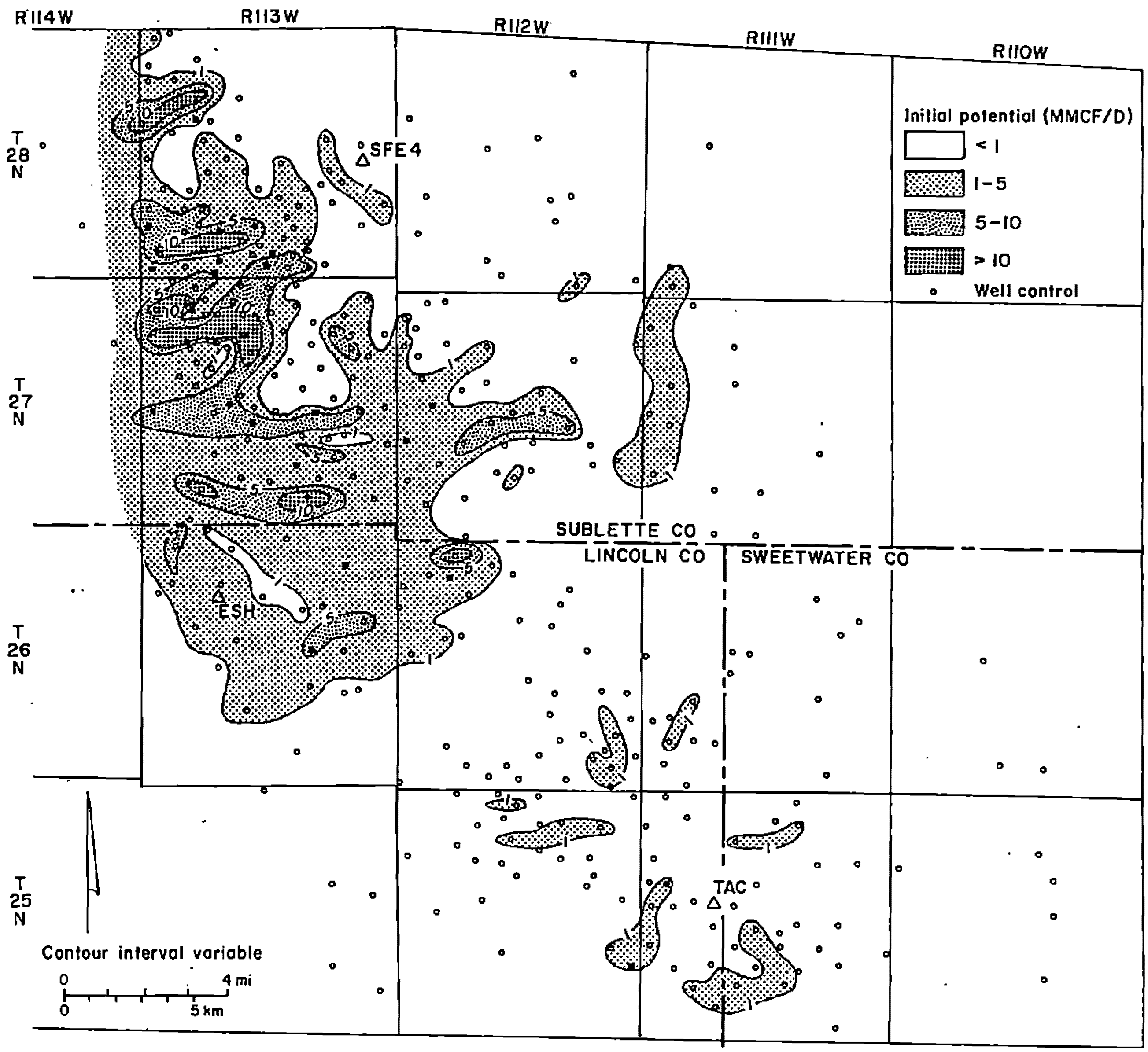

Figure 16. Initial potential map of wells on the La Barge Platform having Second Bench perforations. These wells commonly have additional perforations in other Frontier zones, and in those cases production is commingled. Locations of S. A. Holditch & Associates Staged Field Experiment No. 4 well (SFE 4), Terra Resources Anderson Canyon No. 3-17 (TAC), and Enron South Hogsback No. 13-8A (ESH) are shown. Wells having perforations in other formations were excluded from this map.

SP deflections. The initial potentials shown on figure 16 are typically measured or calculated after the wells received a hydraulic fracture treatment, and variations in the effectiveness of these stimulation treatments can influence well productivity. Natural fractures may be important to Second Bench productivity, but the location, abundance, and orientation of natural fractures in the subsurface is difficult to measure directly (Laubach, 1991). Finally, commingling of gas production from several Frontier zones is common and further obscures causal relationships, although the Second Bench is typically the dominant contributor in such cases.

GRI COOPERATIVE WELLS

Core and log data gathered in GRI/industry cooperative wells allowed field-scale and well-site studies of Frontier reservoir sandstones at several locations along the Moxa Arch (fig. 1).

Terra Resources Anderson Canyon No. 3-17

The Terra Resources (now Pacific Enterprises) Anderson Canyon No. 3-17 cooperative well is located at Fontenelle field on the southeastern margin of the La Barge Platform (fig. 2). Fontenelle field lies in a broad, unfaulted, structural nose, which dips 200 ft/mi (2°) to the southeast. Continuous core was taken in Terra Anderson Canyon No. 3-17 from 9,015 to 9,188 ft. The cored interval includes the lower First Bench, all of the Second Bench, and a small part of the upper Fourth Bench (fig. 10).

The deepest core recovered is about 15 ft of shale and sandy shale (9,172.5 to 9,188 ft) from below the Second Bench, which displays the indistinct mottling and root traces commonly observed in soil profiles. This is the uppermost part of Fourth Bench coastal-plain depositional facies. The Third Bench is generally not distinguishable at Fontenelle field (fig. 10). A sharp erosional surface occurs at 9,172.5 ft and is overlain by bioturbated shaly sandstone in the lower part of the Second Bench. This surface, which forms the lower boundary of the Second Bench shoreface sequence throughout the La Barge Platform, was cut into the underlying Fourth Bench by shoreface erosion that accompanied westward shoreline retreat. Truncation of the Fourth Bench apparently increases toward the southeast (fig. 10).

At the Terra Anderson Canyon No. 3-17 well site, the Second Bench is a well-developed progradational shoreface sequence, comprising 74 ft of lower shoreface shaly sandstone (9,098 to 9,172.5 ft) overlain by 20 ft of upper shoreface clean sandstone (9,078 to 9,098 ft, fig. 17). The lower shoreface facies are thoroughly bioturbated mixtures of sand, silt, and clay; primary stratification was destroyed by burrowing organisms. Clay content decreases gradationally upward, ranging from 50 to 10 percent of rock volume. This upward cleaning reflects gradual shoaling as the shoreline approached the position of this well. The upper part of the lower shoreface contains 1- to 2-ft-thick clean sandstone beds that were deposited during storms. The upper shoreface facies comprise clean, well-sorted sandstone having prominent horizontal lamination and crossbeds. The upper shoreface facies were deposited in shallow water where wave- and wind-driven currents agitated and winnowed the bottom sediments and inhibited the activity of burrowing organisms.

The Second Bench is capped by a shale (9,057 to 9,074 ft, fig. 17), having a widespread distribution and a complex depositional history. This shale, together with a 3-ft transition zone of bioturbated shaly sandstone at the top of the Second Bench, apparently records an episode of relative sea-level rise, partial flooding and reworking of the upper part of the shoreface sequence, and then relative sea-level fall accompanied by a return to a coastal-plain setting. Most of this interval (9,070 to 9,057 ft) contains well-developed root mottling and abundant plant debris indicative of a heavily vegetated, floodplain environment.

On the La Barge Platform, First Bench fluvial channel-fill sandstone commonly overlies the organic-rich nonmarine shale described above. At the Terra Anderson Canyon cooperative well, a 19-ft channel-fill sandstone was cored (9,034 to 9,053, fig. 17). An erosional base and internal erosional surfaces, mud-clast conglomerates, large crossbeds, and soft-sediment deformation are distinctive features of the First Bench sandstone from the Terra Anderson

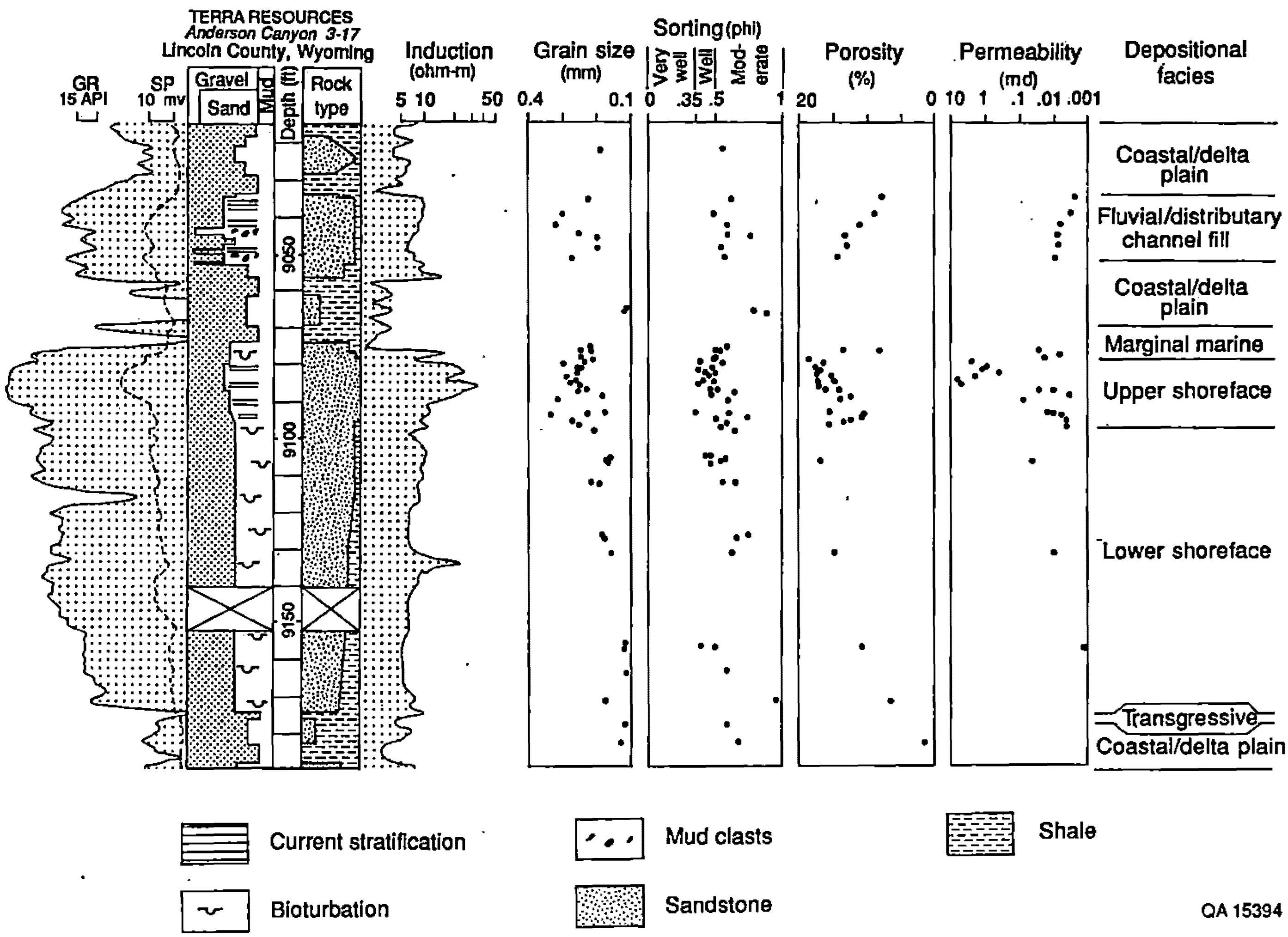

Figure 17. Log responses and rock properties in core from the First and Second Benches of the Second Frontier (fig. 10), Terra Anderson Canyon No. 3-17 well, Fontenelle field (from Dutton and Hamlin, 1991). Porosity and stressed permeability data from core are shown.

Canyon well. The sand-sized fraction in the First Bench is coarser and less well sorted than it is in the Second Bench (fig. 17). Clay volume in this First Bench sandstone averages about 10 percent and occurs mainly as sand- and gravel-sized rip-up mud clasts, which were eroded from the muddy river banks and incorporated into the sandy bed load of the river channel. A zone in the middle part of the sandstone (9,044 to 9,050 ft) contains several 1-ft beds in which volume of mud clasts exceeds 50 percent. A higher gamma-ray response marks this clay-rich zone (fig. 17). First Bench channel-fill sandstone is overlain by channel-flank shaly sandstone and shale in the uppermost part of the core.

At Terra Anderson Canyon No. 3-17, as is the case with many of the wells in Fontenelle field, the Second Bench is the primary reservoir. The pay zone is about 7 ft thick (9,079 to 9,086 ft, approximate core depth) and lies within Second Bench upper shoreface facies. This zone is distinguished by higher core permeabilities than those in adjacent, apparently similar, upper shoreface sandstone (fig. 17), and it contains a lower percentage of ductile rock fragments than does closely adjacent sandstone (Dutton, 1991). These factors, along with subtle variations in stratification type, suggest that the pay zone was deposited either in a foreshore (intertidal) environment or in a very high energy subenvironment of the upper shoreface. The strong bottom currents in this environment winnowed not only the silts and clays but also the less durable sand-sized particles (Dutton, 1991). Clearly, depositional environment exerted a strong control on reservoir quality in the Frontier at the Terra Anderson Canyon well site.

Wexpro Church Buttes Unit No. 48

The Wexpro Church Buttes Unit No. 48 cooperative well is located in Church Buttes field along the southern part of the Moxa Arch (fig. 2). The field lies in a north-trending, doubly plunging anticline, which is about 14 mi long and coincides with the crest of the Moxa Arch. The Church Buttes cooperative well is located on the north end of the anticline near the fold hinge. The top of Frontier sandstone is at 12,153 ft in this well. A single Second Frontier sandstone interval is present in this area. Core was taken in marine shale above the sandstone (12,045 to 12,072 ft) and through most of the Second Frontier sandstone (12,144 to 12,204 ft).

At Wexpro Church Buttes Unit No. 48, the Second Frontier sandstone comprises a progradational shoreface sequence truncated by a fluvial channel. The lower part of the core (12,177 to 12,204 ft) consists of bioturbated lower shoreface shaly sandstone in which stratification was almost completely destroyed by pervasive burrowing. Upwardly increasing grain size and sandstone percent are well displayed (fig. 18). The lower shoreface is capped by 2 ft of marine mudstone, which is abruptly overlain by fluvial channel-fill sandstone (12,161 to 12,175 ft) containing abundant mud clasts, crossbeds, soft-sediment deformation, and upwardly decreasing grain size (fig. 18). A heterogeneous suite of nonmarine, organic-rich shale and thin sandstone (12,144 to 12,161 ft) overlies the fluvial channel-fill sandstone.

Regional stratigraphic correlations indicate that, along the southern part of the Moxa Arch, the Second Bench shoreface sequence was erosionally truncated by downcutting First Bench fluvial channels. Studies of cores such as this one reveal a shoreline sequence in which the upper shoreface and transitional-marine facies are commonly missing, and fluvial channel-fill sandstone rests directly on offshore marine facies. This erosional unconformity can be traced northward on well logs into the shale that separates the Second and First Benches on the La Barge Platform. Erosional truncation and interval thinning increase southward along the Moxa Arch (fig. 5), indicating that subsidence increased northward during Frontier deposition.

The geometry and quality of Frontier reservoirs are affected by these variations in deposition and erosion. Along the southern part of the Moxa Arch, where upper shoreface facies are commonly missing, First Bench fluvial channel-fill sandstone forms the primary reservoir facies (Moslow and Tillman, 1986, 1989). First Bench fluvial sandstone forms dip-oriented, laterally discontinuous reservoirs, whereas Second Bench shoreface sandstone reservoirs are strike-aligned and more continuous (figs. 11 and 12). At the Wexpro Church Buttes cooperative well site, the upper part of the fluvial channel fill (12,161 to 12,167 ft) has the highest core (stressed) permeabilities (0.28 to 0.79 md), probably because the upper fluvial

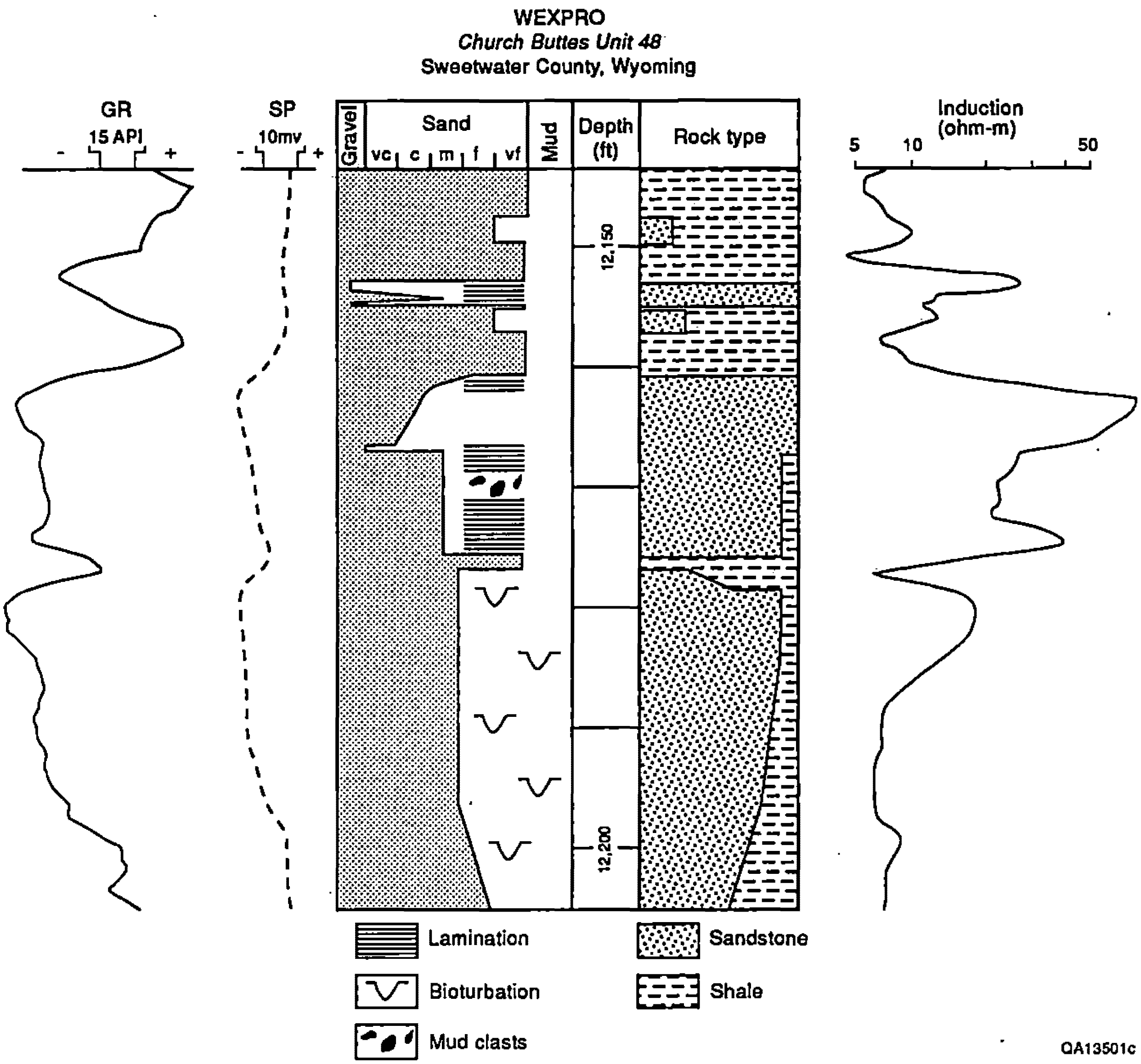

Figure 18. Log responses and core description, Wexpro Church Buttes Unit No. 48 well, Church Buttes field (fig. 2). The core includes bioturbated sandstone (Second Bench) overlain by laminated, mud-clast-bearing sandstone (First Bench).

channel-fill sandstone is coarser grained and contains much fewer mud clasts than the lower part (fig. 18). Lesser quality reservoir rock exists in the lower part of the channel fill and the upper part of the lower shoreface (approximately 12,167 to 12,187 ft), where core (stressed) permeabilities average 0.23 md.

Enron South Hogsback No. 13-8A

The Enron South Hogsback No. 13-8A cooperative well is located in South Hogsback field on the western part of the La Barge Platform (fig. 1). The easternmost of the major Thrust Belt faults (Darby Thrust) crops out near this well. In the South Hogsback field, Frontier strata are folded into a south-plunging anticline between two smaller reverse faults (fig. 19). Several reverse faults in the Hilliard Shale intersect the Enron South Hogsback cooperative well. Nearly continuous core was taken in this well from 7,007 to 7,285 ft. The cored interval includes the First through the Fourth Benches of the Second Frontier (fig. 10).

The Fourth Bench fluvial channel-fill sandstone is 30 ft thick (7,240 to 7,270 ft) and contains features that typify Frontier fluvial channel-fill facies: erosional surfaces, upwardly decreasing grain size, large crossbeds, mud rip-up clasts, and soft-sediment deformation. Clay volume increases from 10 percent near the base to 30 percent near the top. Porosity averages 9 percent, and permeability is less than 0.01 md (from core analysis). The Fourth Bench sandstone is enclosed in nonmarine and transitional-marine, organic-rich shale, sandy shale, and bentonite, which cause very high (off-scale) gamma-ray responses (fig. 10). The same transgressive surface that was cored in the Terra Anderson Canyon cooperative well occurs in the shale that overlies the Fourth Bench in this well (fig. 10).

At Enron South Hogsback No. 13-8A, the Second and Third Benches form a single thick marine shoreline sandstone (7,109 to 7,207 ft), which is composed of two progradational shoreface sequences (fig. 20). The Third Bench comprises bioturbated lower shoreface shaly sandstone (7,185 to 7,207 ft) overlain by upper shoreface clean sandstone (7,171 to 7,185 ft),

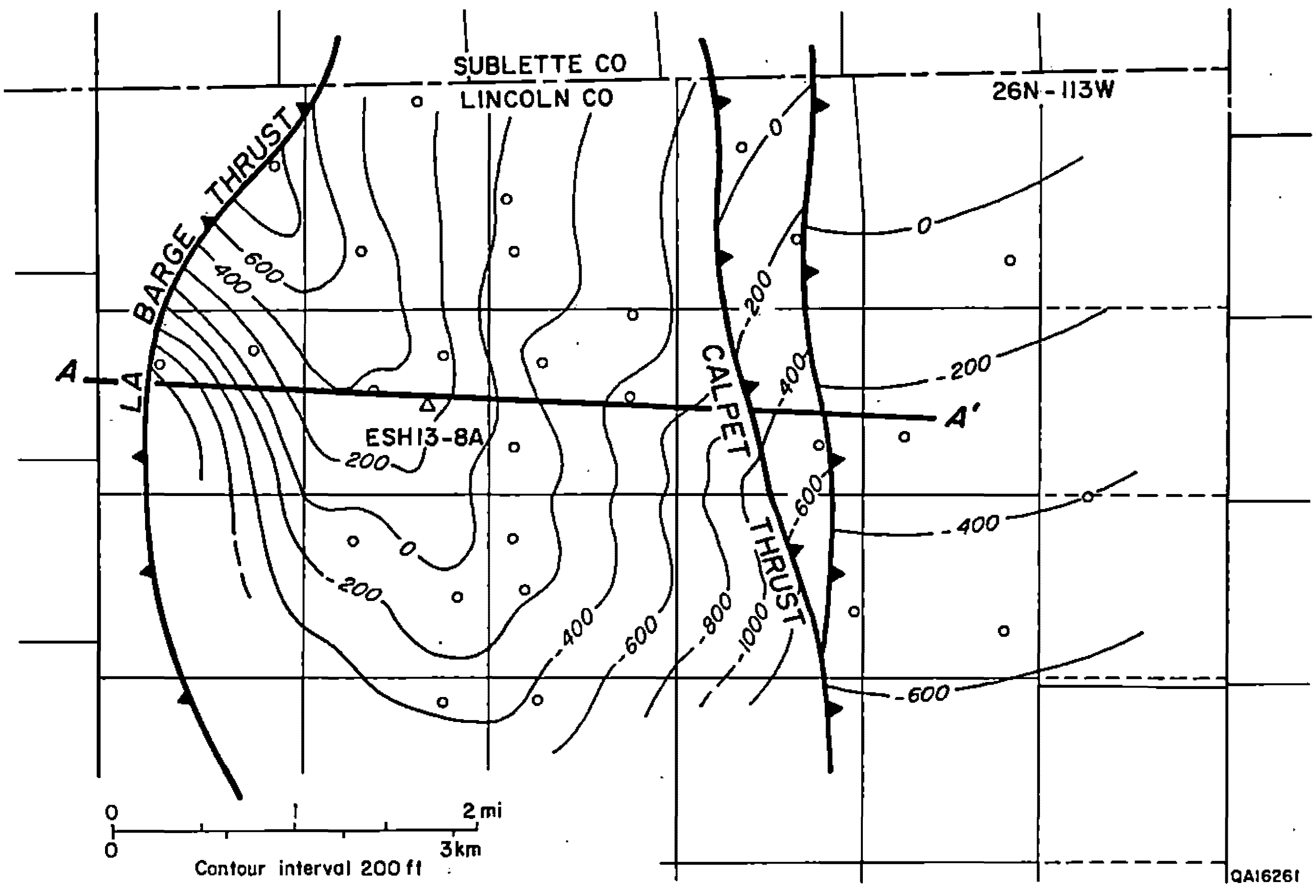

Figure 19. Structure-contour map on the top of the Second Frontier, South Hogsback field. Location of Enron South Hogsback No. 13-8A well (ESH 13-8A) is also shown. The positions of the La Barge and Calpet thrust faults (Blackstone, 1979) are shown at the mapped horizon. The much larger Darby Thrust carries Paleozoic rocks to the surface near the Enron well.

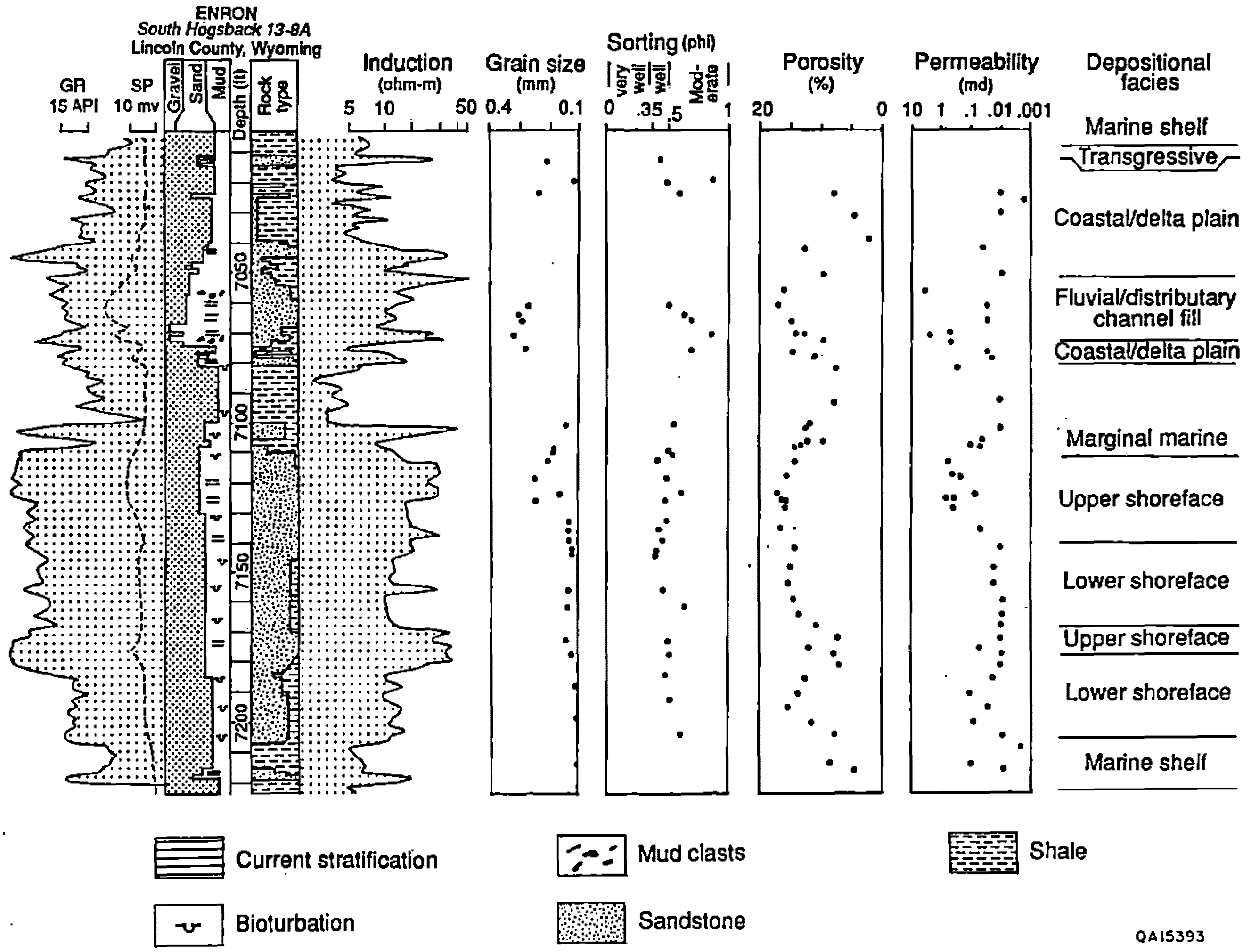

Figure 20. Log responses and rock properties in core from the First, Second, and Third Benches of the Second Frontier (fig. 10), Enron South Hogsback No. 13-8A well, South Hogsback field. Porosity and stressed permeability data from core are shown.

although the upper shoreface contains local shale laminations and abundant carbonate cement. Second Bench lower shoreface shaly sandstone (7,145 to 7,171 ft) directly overlies the Third Bench and is, in turn, overlain by Second Bench upper shoreface clean sandstone (7,113 to 7,145 ft). The Second Bench upper shoreface has the highest core permeabilities in this sandstone (fig. 20).

The Second Bench is overlain by 8 ft of interbedded sandstone and shale (7,101 to 7,109 ft) having abundant bioturbation and oyster shells in the upper 2 ft. The oyster shells are overlain by 19 ft (7,082 to 7,101 ft) of marine and marginal-marine shale. This shale caps the Second Bench throughout the La Barge Platform (fig. 10), although it appears to be more marine-dominated in the Enron South Hogsback well than it is in the Terra Anderson Canyon well.

At the Enron South Hogsback cooperative well site, the First Bench comprises a fluvial channel-fill sandstone enclosed in coastal-plain shale and thin sandstone (fig. 20). The lower part of the channel-fill sandstone (7,067 to 7,075 ft) includes large mud rip-up clasts and coal fragments, which together make up 10 to 70 percent of the rock volume. The upper part of the channel-fill sandstone (7,060 to 7,067 ft) consists of crossbedded sandstone having about 20 percent sand-sized clay clasts. Abundant mud rip-up clasts significantly limit First Bench reservoir quality on the La Barge Platform. Locally high core (stressed) permeabilities (0.5 to 1.5 md) in the First Bench in this well (fig. 20) occur in isolated thin zones.

A thick (7,015 to 7,060 ft) zone of root-mottled organic-rich shaly sandstone and sandy shale lies between the First Bench channel-fill sandstone and marine sandstone and shale contained in the uppermost 8 ft of core. A thin transgressive marine sandstone (7,012.5 to 7,014.5 ft, fig. 20) marks the top of the Second Frontier in the Enron South Hogsback cooperative well.

Perforations (7,110 to 7,202 ft) extend across both the Second and Third Benches in Enron South Hogsback No. 13-8A, encompassing lower and upper shoreface facies. Core permeabilities, however, are generally very low throughout the perforated interval, except in a

17-ft-thick zone (7,113 to 7,130 ft) within the Second Bench upper shoreface, where stressed permeability averages 0.36 md (fig. 20). Unlike the Terra Anderson Canyon well, no high-energy subenvironment or foreshore facies appears within the upper shoreface in the Enron South Hogsback cooperative well.

S. A. Holditch & Associates SFE No. 4-24

The Staged Field Experiment (SFE) No. 4 well is a research well drilled by GRI on leases acquired through the cooperation and assistance of Enron Oil and Gas Company. SFE No. 4 is located in Chimney Butte field on the northeast flank of the La Barge Platform (fig. 1), where the Frontier dips 300 ft/mi (3°) to the northeast. More than 300 ft of core was taken between a depth of 6,777 and 8,004 ft. Marine shales were cored in the Hilliard (above and below the First Frontier) and in the Mowry below the Fourth Frontier (fig. 4). Most of the Second Frontier and the Third Frontier were also cored.

At the SFE No. 4 well site, the lower part of the First Bench of the Second Frontier includes about 12 ft of interbedded clean sandstone, mud-clast-rich sandstone, and shale, which apparently were deposited in a small fluvial channel. Another thin sandstone occurs in the upper part of the First Bench but was not cored. The Second Bench consists of 14 ft of relatively clean, upper shoreface sandstone, which is overlain and underlain by lower shoreface shaly sandstones. The entire Second Bench is only about 45 ft thick at this location. Cores from the Fourth and Fifth Benches contain no clean sandstone but are dominated by thick intervals of root-mottled, organic-rich, shaly sandstone and sandy shale. The Third Frontier consists of about 30 ft of interbedded clean and shaly, carbonate-cemented sandstone of apparent shoreface origin.

The reservoir in the SFE No. 4 well is limited to a 12-ft zone within the Second Bench upper shoreface clean sandstone (7,400 to 7,412 ft). Core (stressed) permeabilities in this zone range from 0.02 to 0.12 md. Low permeability apparently results from quartz and calcite cementation (Dutton, 1991). The limited development of upper shoreface facies, combined with diagenetic porosity and permeability reduction, restricts the potential gas productivity of this well.

CONCLUSIONS

The main depositional and stratigraphic controls on distribution and quality of Frontier reservoirs are sandstone continuity and detrital clay content. Frontier production trends reflect sandstone distribution and continuity. The Second Frontier was deposited in a fluvial-deltaic system having prominent delta-flank strandplains. Marine shoreface and fluvial channel-fill sandstones are the reservoir facies. Second Bench shoreface sandstone is continuous across the La Barge Platform, where most Frontier wells have Second Bench perforations. The First Bench contains numerous discontinuous fluvial channel-fill sandstones, and only wells penetrating these channels typically have First Bench production. However, First Bench channel-fill sandstones are the primary reservoir facies along the southern part of the Moxa Arch (Moslow and Tillman, 1986, 1989), where Second Bench upper shoreface sandstone is commonly absent, owing to erosional truncation. The other lower Frontier zones, which were deposited in mud-dominated coastal plain and marine shoreline systems, contain isolated sandstones that are locally productive.

Detrital clay content exerts a strong influence on the porosity and permeability of Frontier sandstone prior to diagenetic modification, and detrital clay content is controlled by depositional environment. Most Frontier sandstones along the Moxa Arch were deposited in one of three depositional environments: lower shoreface, upper shoreface, and fluvial channel. Frontier lower shoreface sandstone is characterized by abundant pore-filling detrital clay matrix, which was mixed into the sand by burrowing organisms on the sea floor. In Frontier lower shoreface sandstone, permeabilities are generally low, although porosities may be similar to those in the other sandstone facies (Dutton, 1991). Frontier upper shoreface sandstone is free of clay at the time of deposition, because in the shallow-water upper shoreface environment, strong currents winnow fine-grained sediment and inhibit burrowing organisms. On the La Barge Platform, the most prolific Frontier reservoirs lie in Second Bench upper shoreface sandstone. Frontier fluvial channel-fill sandstone contains abundant sand- and gravel-sized mud rip-up clasts, which deform into pores and pore throats during compaction. The channel-fill facies typically consist of mud-clast-rich sandstone interlayered with and laterally gradational with sandstone that is relatively free of mud clasts. Thus, clean sandstone typically forms discontinuous lenses within the channel-fill facies. Upper shoreface clean sandstone, on the other hand, consistently occurs at the top of the progradational shoreface sequence and therefore forms a more predictable target.

ACKNOWLEDGMENTS

Funding for this study was provided by the Gas Research Institute under contract number 5082-211-0708 (Mark R. Johnson, project manager). Donations of cores, well logs, and other data by Pacific Enterprises, Enron, Wexpro, Texaco, and Mobil form an important part of the data base for this study and are gratefully acknowledged. I thank the Geologic Survey of Wyoming for compiling a large volume of Frontier production data. R. L. Buehring, J. Kopf, and G. A. Klimchuk assisted in various phases of the project. I have benefited from discussions about the Frontier Formation with W. A. Ambrose, W. B. Ayers, Jr., S. P. Dutton, W. E. Galloway, S. E. Laubach, and R. A. Morton. I appreciate helpful reviews of this report by W. B. Ayers, Jr., S. P. Dutton, and M. R. Johnson. Figures in this report were prepared under the direction of R. L. Dillon, chief cartographer. Margaret L. Evans was designer. Word processing was by Melissa Snell and Susan Lloyd, and editing was by Bobby Duncan under the direction of Susann Doenges, editor in chief.

REFERENCES

Baumgardner, R. W., Jr., Tye, R. S., Laubach, S. E., Diggs, T. N., Herrington, K. L., and Dutton, S. P., 1988, Site selection for GRI cooperative tight gas field research, vol. II: Geologic characteristics of selected low-permeability gas sandstones: The University of Texas at Austin, Bureau of Economic Geology, topical report prepared for the Gas Research Institute under contract no. 5082-211-0708, 225 p.

Blackstone, D. L., Jr., 1979, Geometry of the Prospect-Darby and La Barge faults at their junction with the La Barge Platform, Lincoln and Sublette Counties, Wyoming: The Geological Survey of Wyoming, Report of Investigations No. 18, 34 p.

Byers, C. W., and Larson, D. W., 1979, Paleoenvironments of Mowry Shale (Lower Cretaceous), western and central Wyoming: American Association of Petroleum Geologists Bulletin, v. 63, p. 354–375.

De Chadenedes, J. F., 1975, Frontier deltas on the western Green River Basin, Wyoming, *in* Bolyard, D. W., ed., Symposium on deep drilling frontiers in the central Rocky Mountains: Rocky Mountain Association of Geologists, p. 149–157.

Dutton, S. P., 1991, Diagenetic controls on reservoir properties of low-permeability sandstone, Frontier Formation, Moxa Arch, southwest Wyoming: The University of Texas at Austin, Bureau of Economic Geology, topical report prepared for the Gas Research Institute under contract no. 5082-211-0708, 48 p.

Dutton, S. P., and Hamlin, H. S., 1991, Geologic controls on reservoir properties of Frontier Formation low-permeability gas reservoirs, Moxa Arch, Wyoming: Proceedings, Society of Petroleum Engineers Joint Rocky Mountain Regional/Low Permeability Reservoirs Symposium, SPE Paper 21851, p. 497–488.

Galloway, W. E., and Cheng, E. S., 1985, Reservoir facies architecture in a microtidal barrier system—Frio Formation, Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations No. 144, 36 p.

Heward, A. P., 1981, A review of wave-dominated clastic shoreline deposits: Earth-Science Reviews, v. 17, p. 223–276.

Laubach, S. E., 1991, Fracture patterns in low-permeability-sandstone gas reservoir rocks in the Rocky Mountain region: Proceedings, Society of Petroleum Engineers Joint Rocky Mountain Regional/Low Permeability Reservoirs Symposium, SPE Paper 21853, p. 501–510.

McDonald, R. E., 1973, Big Piney–La Barge producing complex, Sublette and Lincoln Counties, Wyoming: 25th Annual Field Conference, p. 57–77.

Merewether, E. A., Blackmon, P. D., and Webb, J. C., 1984, The mid-Cretaceous Frontier Formation near the Moxa Arch, southwestern Wyoming: U.S. Geological Survey Professional Paper 1290, 29 p.

Molenaar, C. M., and Wilson, B. W., 1990, The Frontier Formation and associated rocks of northeastern Utah and northwestern Colorado: U.S. Geological Survey Bulletin 1787-M, p. M1–M21.

Moslow, T. F., and Tillman, R. W., 1986, Sedimentary facies and reservoir characteristics of Frontier Formation sandstones, southwestern Wyoming, *in* Spencer, C. W., and Mast, R. F., eds., Geology of tight gas reservoirs: American Association of Petroleum Geologists Studies in Geology No. 24, p. 271–295.

__________ 1989, Characterization, distribution of Frontier formation reservoir facies of Wyoming fields: Oil and Gas Journal, v. 87, p. 95–103.

Myers, R. C., 1977, Stratigraphy of the Frontier Formation (Upper Cretaceous), Kemmerer area, Lincoln County, Wyoming: Wyoming Geological Association Guidebook, 29th Annual Field Conference, p. 271–311.

Schultz, M. S., and Lafollette, R. F., 1989, Effect of drilling and completion methods on Frontier gas production, northern Moxa Arch, southwest Wyoming: Wyoming Geological Association Guidebook, 40th Annual Field Conference, p. 247–254.

Thomaidis, N. D., 1973, Church Butte's arch, Wyoming and Utah: Wyoming Geological Association Guidebook, 25th Annual Field Conference, p. 35–39.

Wach, P. H., 1977, The Moxa Arch, an overthrust model?: Wyoming Geological Association Guidebook, 29th Annual Conference, p. 651–664.

Wiltschko, D. V., and Dorr, J. A., 1983, Timing of deformation in overthrust belt and foreland of Idaho, Wyoming, and Utah: American Association of Petroleum Geologists Bulletin, v. 67, p. 1304–1322.

Wiltschko, D. V., and Eastman, D. B., 1983, Role of basement warps and faults in localizing thrust fault ramps, *in* Hatcher, R. D., Jr., Williams, H., and Zietz, I., eds., Contributions to the tectonics and geophysics of mountain chains: Geological Society of America Memoir 158, p. 177–190.

Winn, R. D., Jr., Stonecipher, S. A., and Bishop, M. G., 1984, Sorting and wave abrasion: controls on composition and diagenesis in lower Frontier sandstones, southwestern Wyoming: American Association of Petroleum Geologists Bulletin, v. 68, p. 268–284.